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NAVAL POSTGRADUATE SCHOOL

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UMD/NPS Free Electron Laser Research

by

Joseph Blau and William B. Colson

1 December 2008

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Prepared for: University of Maryland
College Park, MD 20742-3511

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13. ABSTRACT (maximum 200 words)
Simulations and theoretical analysis are used to study the development of high-average-power free electron lasers (FELs). Various existing and proposed FELs are studied, in both amplifier and oscillator configurations. Comparisons to experimental results show good agreement in each case.

At the outset of this project, short Rayleigh length (SRL) optical cavities were proposed to reduce the optical intensity on the mirrors. Contrary to conventional wisdom, our simulations showed that an SRL FEL would have good gain and power extraction. This was recently confirmed experimentally at Jefferson Laboratory.

System sensitivity to misalignments and distortions are also studied, and tolerance limits are established for tilts and shift of various components such as the mirrors, electron beam, and magnetic quadrupoles. These tolerances have already been readily achieved in laboratories using active alignment.

The research done over 8 years on this project has resulted in 19 published papers, 21 M.S. theses, 2 Ph.D. dissertations, and 26 conference presentations, which are summarized in this report.

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I. INTRODUCTION

The overall goal of this collaboration between the Naval Postgraduate School and the University of Maryland is scientific contributions to the development of a MW-class free electron laser (FEL) for naval applications. During the 8 years that we worked on this project, we published 19 papers on our research results, our students produced 21 Master of Science in Physics theses and 2 Physics Ph.D. dissertations, and we gave 26 presentations at 11 international conferences and symposia.

Over the course of this project, we simulated various existing free electron lasers (FELs), including the Jefferson Lab (JLab) 10kW oscillator FEL and the Brookhaven amplifier FEL. We made predictions and comparisons to experimental results, with good agreement in each case. We developed designs for high-power FELs, including 100 kW and MW-level amplifiers and oscillators. We found feasible sets of parameters for these designs, which formed the basis for the recently approved Innovative Naval Prototype (INP). We did system analysis studies of ship-based FEL weapons, including power requirements and integration with other weapon systems such as railguns.

An important aspect of our research has been the design of short-Rayleigh length (SRL) optical cavities for high-power FEL oscillators, to reduce the optical intensity on the cavity mirrors. At the outset of this project, we predicted that, contrary to conventional wisdom in the FEL community, the weak-field gain and steady-state power should not fall off significantly for extremely short Rayleigh lengths. These predictions were recently confirmed by experiments at JLab.

A major concern for SRL cavities is the stability of the optical mode, and sensitivity to tilts and shifts of the mirrors and electron beam. Simple cold-cavity theory predicts that an SRL FEL could be highly sensitive to such misalignments, but our simulations have shown that the gain medium, the electron beam, tends to stabilize the optical mode, significantly reducing the system sensitivity to misalignments. These results were also confirmed by experiments at JLab. We have used our simulations to establish tolerances for tilts and shifts of the mirrors and electron beam for various high-power FEL designs. The expected tolerances have been readily achieved in laboratory experiments using active alignment mechanisms.

A laser weapon system on a Naval platform would be subject to vibrations from various sources. Since these vibrations tend to occur on acoustic timescales (milliseconds), whereas the interaction of the electron and optical pulses occur on much shorter timescales (microseconds to nanoseconds), we can simulate the effects of vibrations using static misalignments. In addition to mirror and electron beam tilts and shifts, we have also considered the effects of misaligned quadrupole magnets along the electron beam path. Again the tolerance limits that we established are well within the range of what can be achieved using active alignment.

Another issue that we studied is the distortion of the optical mirrors, such as astigmatism, that can occur in high-power FELs. We simulated the effects of these distortions, and compared the results to JLab experiments, with good agreement. We also developed methods for modal analysis of the optical beam, using Hermite-Gaussian and Laguerre-Gaussian basis sets, which could be useful for optical transport calculations in designing FEL weapon systems.

To accomplish all these tasks, we have made significant improvements in our FEL simulation models. This includes the development of new, parallelized 3D and 4D models that run on a cluster computer, and implementation of an expanding coordinate system to follow the rapid diffraction of the optical beam in an SRL FEL. These new models have been tested and benchmarked by comparison to theoretical formulas, simpler 1D and 2D models, and experimental results. We also developed a ray analysis of SRL optical modes, as an alternative to our wavefront propagation models.

Finally, it should be emphasized that this research project has contributed significantly to the education of numerous U.S. Navy officers. Their participation in this project has helped to teach them how FELs work, their various features and design issues, and the potential advantages of incorporating them into naval weapon systems.

The remainder of this report consists of one-page summaries of each of the papers, presentations, theses and dissertations that were produced over the course of this project. At the top of each page, there is a reference or a web link (where available) to obtain the complete article or presentation. Electronic copies of NPS theses and dissertations can be obtained from the Defense Technical Information Center, http://www.dtic.mil. Proceedings of FEL conferences since 2004 can be obtained at http://www.jacow.org.

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Nuclear Instruments and Methods in Physics Research A 475 (2001) 178–181

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Simulations of the TJNAF 10 kW free electron laser

R.D. McGinnis, J. Blau, W.B. Colson*, D. Massey, P.P. Crooker[1], A. Christodoulou, D. Lampiris

Department of Physics, Naval Postgraduate School, Monterey, CA 93943, USA

Abstract

The TJNAF Free Electron Laser (FEL) will be upgraded to operate at 10 kW average power in the near future. Multimode simulations are used to analyze the operation describing the evolution of short optical pulses in the far infrared wavelength regime. In an FEL that recirculates the electron beam, performance can depend on the electron beam distribution exiting the undulator. The effects of varying the undulator field strength and Rayleigh length of the resonator are explored, as well as the possibility of using an optical klystron. The simulations indicate that the FEL output power can reach the design goal of 10 kW.

PACS: 41.60Cr

Keywords: Free-electron laser; Klystron; Rayleigh length

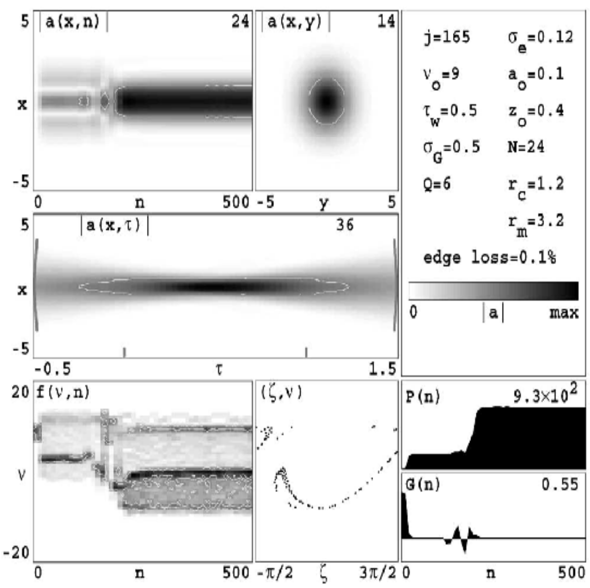

Fig. 3. Three dimensional simulation in x, y, and τ over many passes n, for normalized Rayleigh length z_0 = 0.4.

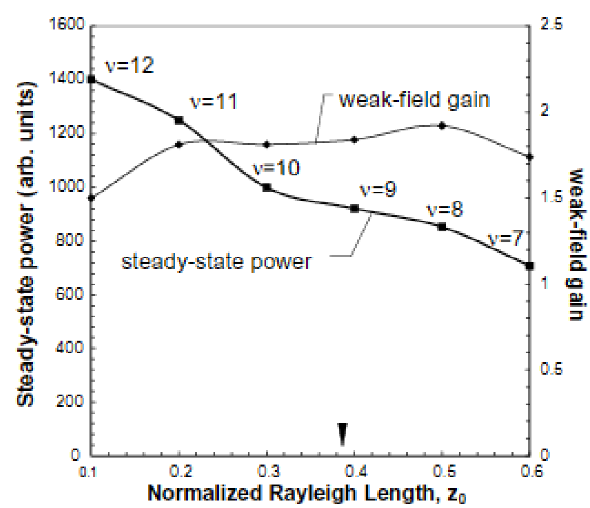

Fig. 4. Three dimensional simulation results for weak-field gain and steady-state power vs. z_0. The optimum resonance parameter ν is indicated at each point.

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Nuclear Instruments and Methods in Physics Research A 475 (2001) 182–186

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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Simulations of the TJNAF FEL with tapered and inversely tapered undulators

A. Christodoulou[a], D. Lampiris[a], W.B. Colson[a,*], P.P. Crooker[a,1], J. Blau[a], R.D. McGinnis[a], S.V. Benson[b], J.F. Gubeli[b], G.R. Neil[b]

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[b] FEL Department, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

Experiments using the TJNAF FEL have explored the operation with both tapered and inversely tapered undulators. We present here numerical simulations using the TJNAF experimental parameters, including the effects of taper. Single-mode simulations show the effect of taper on gain. Multimode simulations describe the evolution of short optical pulses in the far infrared, and show how taper affects single-pass gain and steady-state power as a function of desynchronism. A short optical pulse presents an ever-changing field strength to each section of the electron pulse so that idealized operation is not possible. Yet, advantages for the recirculation of the electron beam can be explored.

PACS: 41.60Cr

Keywords: Taper; Inverse taper; Free-electron laser; Simulation

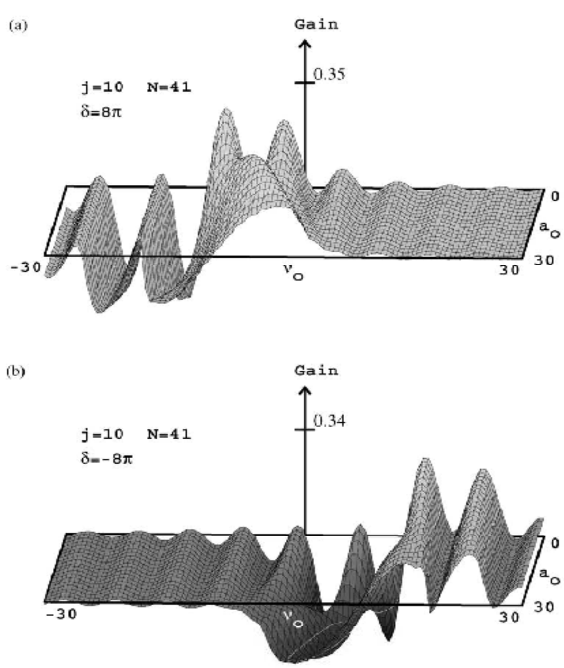

Fig. 1. FEL gain spectrum $G(\nu_0, a_0)$ for large tapers. (a) $\delta = +8\pi$; (b) $\delta = -8\pi$.

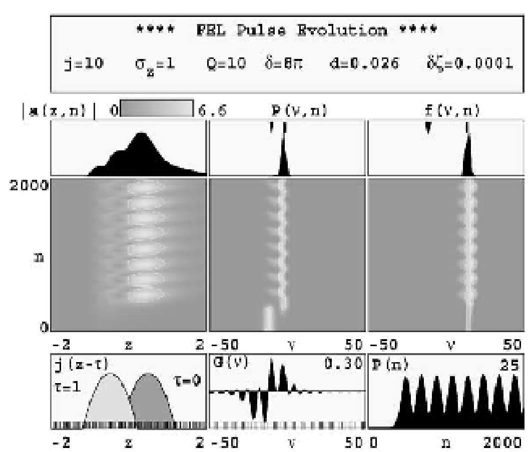

Fig. 2. Multimode simulation for $j = 10$, $d = 0.026$, and $\delta = +8\pi$. The various quantities are explained in the text. In this case, the oscillations in $|a(z,n)|$, $P(\nu,n)$, $f(\nu,n)$, and $P(n)$ are evidence for limit-cycle behavior.

SIMULATIONS OF THE 100kW TJNAF FEL USING A SHORT RAYLEIGH LENGTH

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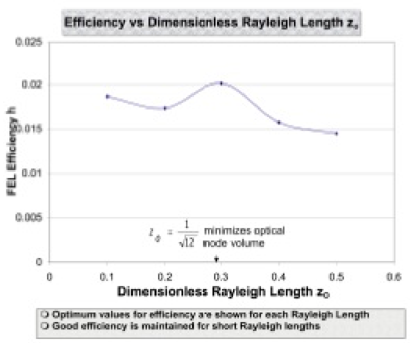
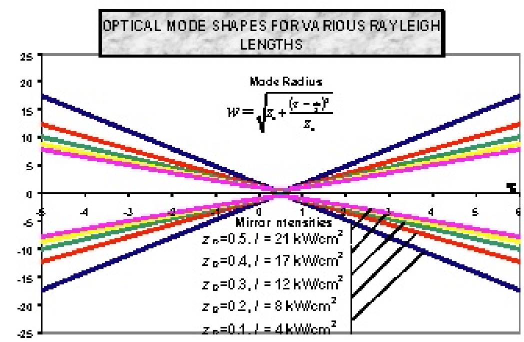
Newport News, Virginia 23606 USA

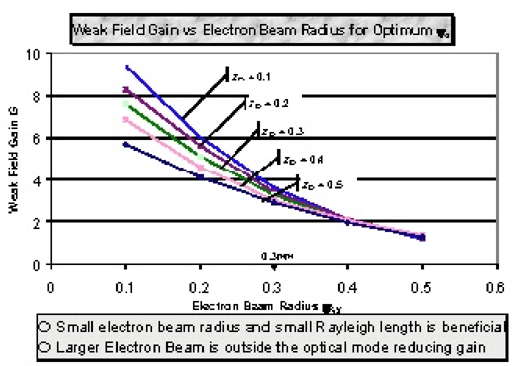
23rd International FEL Conference, Darmstadt, Germany, August 20-24, 2001

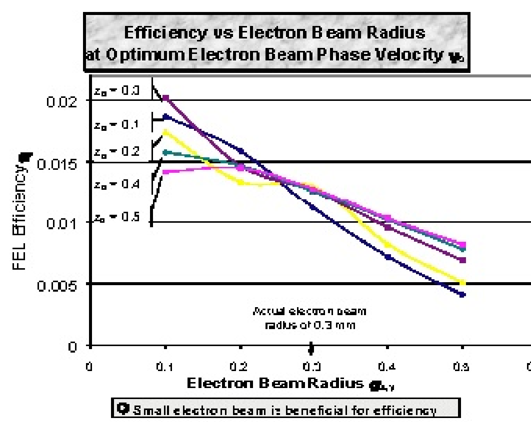
ABSTRACT

- The TJNAF FEL can be upgraded to 100kW avg power
- Short Rayleigh length can reduce mirror power density
- Use multimode simulations to model FEL interaction
- Explore effect of electron beam radius on gain, efficiency









SIMULATIONS OF THE 100 kW TJNAF FEL USING A STEP-TAPERED UNDULATOR

J. Blau, V. Bouras, W.B. Colson, A. Kalfoutzos, K. Polykandriotis

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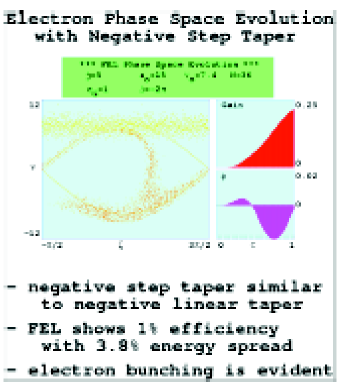
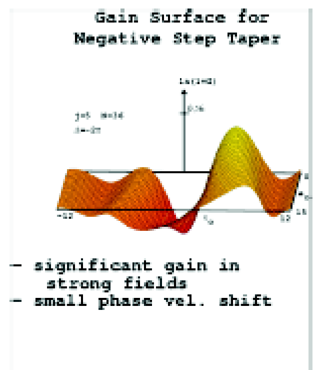
Thomas Jefferson National Accelerator Facility
Newport News, VA 23606 USA

23rd International FEL Conference, Darmstadt, Germany, August 20-24, 2001

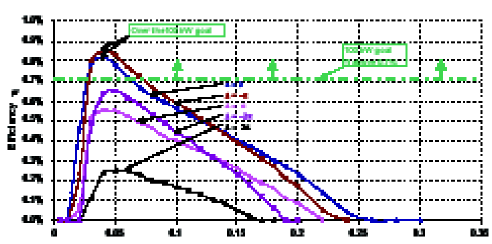
ABSTRACT

- We present simulations of the TJNAF FEL experiments including the effects of step-taper.
- We explore the effects of step-taper on gain, power, efficiency, and desynchronism.
- Investigate energy spread for safe electron beam recirculation
- Comparisons are made to conventional periodic, linearly and step- tapered undulators.



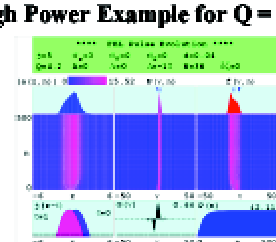


Efficiency η(d) for Step-taper , Q = 4.2



- TJNAF FEL Power above 100kW for Δ=0,−π !!! (required d<0.07)

High Power Example for Q = 4.2



- Negative step taper increases efficiency
- Efficiency is η = 0.86 % , corresponding to power of 116 kW
- Induced energy spread is Δγ/γ = 2.4%

SIMULATIONS OF THE PROPOSED TJNAF 100KW FREE ELECTRON LASER AND COMPARISON WITH TJNAF LOW POWER EXPERIMENTS

by

Konstantinos Polykandriotis

December 2001

Thesis Advisor: William B. Colson
Co-Advisor: Robert L. Armstead

One transitional step for the development of a 1 MW power directed energy weapon is the proposed 100 kW upgrade of the Thomas Jefferson National Accelerator Facility's Free Electron Laser (FEL). To improve the performance of the FEL, the use of the step-taper undulator is explored. Steady-state gain, final steady-state power, and the induced electron spread as a function of desynchronism and taper rates are determined. Comparisons are made to the conventional periodic and linearly tapered undulators. The multimode simulations used showed that the TJNAF 100kW FEL is feasible. Simulations results with Q =10 show that the inverse step-taper undulator $\Delta = -\pi$ achieved the highest final power of 190 kW at a desynchronism value of d = 0.01, while maintaining the induced energy spread well below the engineering limit. The validity of our results is verified against experiments conducted in the TJNAF FEL facility. The simulations and the experimental data are in good agreement and consistent with analytic theory.

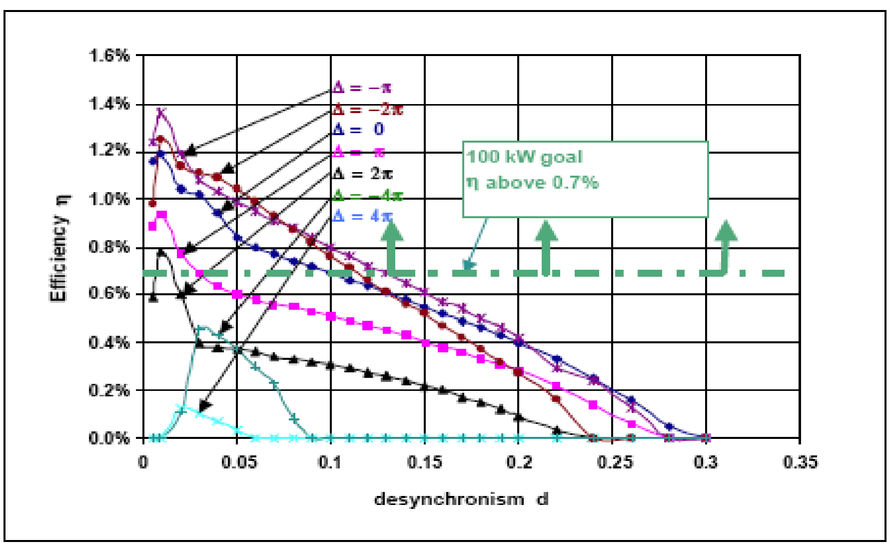


Figure 23. Efficiency η versus Desynchronism d for Step-Taper, and Higher Q=10. Power Above 100 kW for a Larger Range of Tapers $\Delta = 0, \pm\pi, \pm 2\pi$.

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Simulations of the 100 kW TJNAF FEL using a short Rayleigh length

J. Blau[a], T. Campbell[a], W.B. Colson[a,*], I. Ng[a], W. Ossenfort[a], S.V. Benson[b], G.R. Neil[b], M.D. Shinn[b]

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[b] Free Electron Laser Department, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

The TJNAF FEL can be upgraded to operate at 100 kW average power and then explore the use of a short Rayleigh length in order to reduce the power density on the resonator mirrors. The short Rayleigh length can only work with a relatively short undulator. Multimode simulations are used to self-consistently model the optical mode interaction with the electron beam. The steady-state resonator mode is affected by the complex, non-linear electron beam evolution as well as the resonator design.

PACS: 41.60Cr

Keywords: Free-electron laser

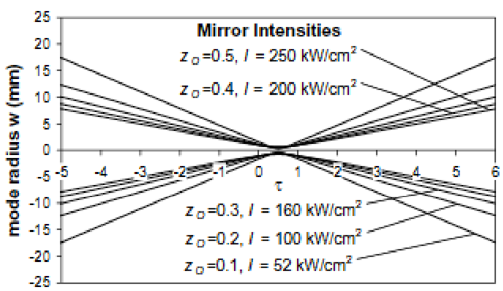

Fig. 1. Optical mode shapes for various Rayleigh lengths. By reducing z_0 from 0.3 to 0.1, a 300% reduction in intensity is experienced at the mirrors.

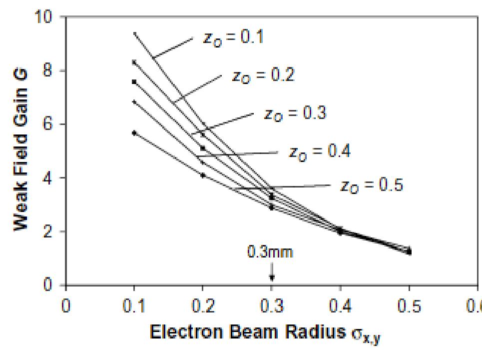

Fig. 3. Weak field gain vs. electron beam radius for optimum w_0. Small electron beam radius and small Rayleigh length was found to be beneficial. A larger electron beam is outside the optical mode thus reducing gain.

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Nuclear Instruments and Methods in Physics Research A 483 (2002) 138–141
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
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Simulations of the 100 kW TJNAF FEL using a step-tapered undulator

J. Blau[a], V. Bouras[a], W.B. Colson[a,*], K. Polykandriotis[a], A. Kalfoutzos[a], S.V. Benson[b], G.R. Neil[b]

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[b] *Free Electron Laser Department, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA*

Abstract

The Thomas Jefferson National Accelerator Facility (TJNAF) free electron laser (FEL) can be upgraded to operate at 100 kW average power in the near future using a configuration that recirculates the electron beam to recover energy. It is important to extract the maximum energy from the electron beam in a pass through the undulator while inducing the minimum amount of exhaust energy spread. A larger energy extraction reduces the requirement for a large recirculating current, while a smaller exhaust energy spread allows the intense electron beam to be recirculated without damaging components. To improve FEL performance, we explore the use of the step-tapered undulator, which alters the resonance condition halfway through the undulator. Short pulses complicate the desired interaction. Comparisons are made to the conventional periodic and linearly-tapered undulators.

PACS: 41.60.Cr

Keywords: Free-electron-laser

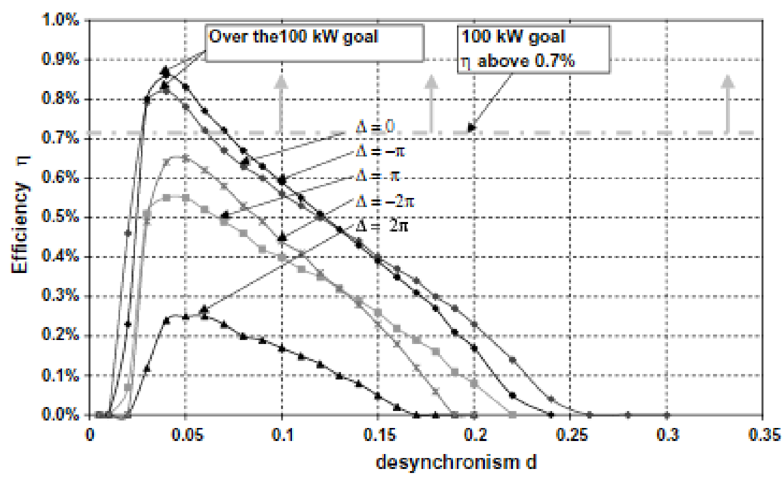


Fig. 2. Efficiency η versus desynchronism d for step taper with $Q = 4.2$. Power above 100 kW for $\Delta = 0, -\pi$.

MULTIMODE SIMULATIONS OF FREE ELECTRON LASERS

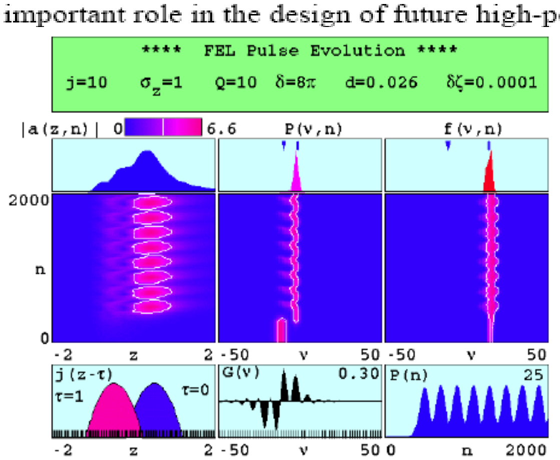
by

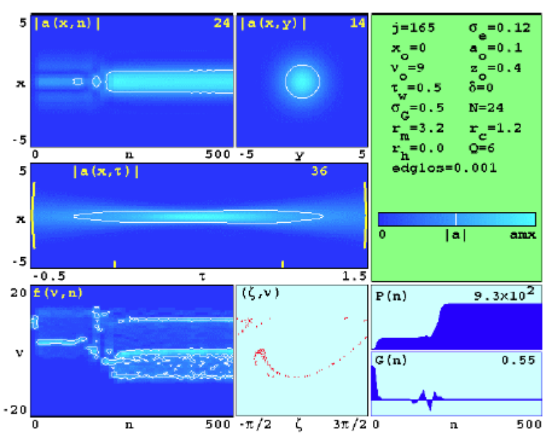
Joseph Blau

March 2002

Dissertation Supervisor: William B. Colson

The results of theoretical research on Free Electron Lasers (FELs) are presented. Basic FEL physics is reviewed, using a previously developed classical theory. Numerical simulations based on this theory are described, and numerous examples show how they have been used to increase understanding of existing FELs and to help plan new experiments. Single-mode simulations that follow the evolution of a single-frequency plane wave provide insight into important physical effects in FELs. Results show how these simulations are used to evaluate new FEL designs such as inverse-tapered and step-tapered undulators. Longitudinal multimode simulations model plane waves using finite-length electron and optical pulses. These simulations are used to study coherence evolution in various FEL designs, and to explain effects such as limit-cycle behavior. Transverse multimode simulations that allow for the finite transverse dimensions of the optical wavefronts include the effects of optical mode distortion. These simulations are currently being used to design short Rayleigh length optical cavities that are less sensitive to mirror damage. Four-dimensional simulations are also described, which follow the optical wavefront in x, y, z, and t, including the effects of multiple longitudinal and transverse modes. These simulations are computationally intensive, but may play an important role in the design of future high-power FELs.





SIMULATIONS OF HIGH-POWER FREE ELECTRON LASERS WITH STRONGLY FOCUSED ELECTRON AND OPTICAL BEAMS

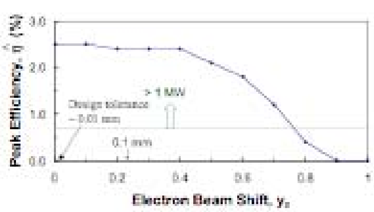
J. Blau, V. Bouras, A. Kalfoutzos,
G. Allgaier, T. Fontana, P.P. Crooker and W.B. Colson
Naval Postgraduate School, Monterey, CA 93943

International FEL Conference, Chicago, IL, Sept 2002

Outline

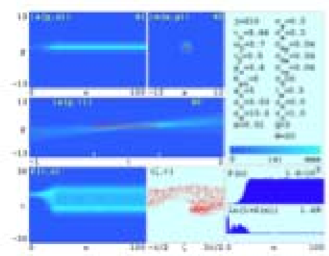
- To avoid mirror damage, high-power FEL requires short Rayleigh length → small optical waist
- Study effects of electron beam misalignment
  - Off-axis shift
  - Tilt about center of undulator
  - Tilt at beginning of undulator
- Study electron beam focusing

Peak Efficiency $\hat{\eta}$ vs Electron Beam Shift y_o



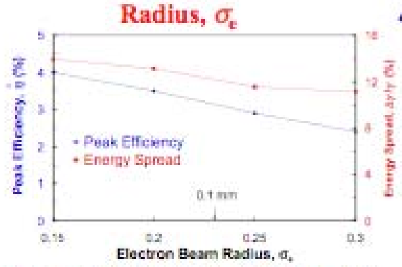
- Efficiency begins to drop for $y_o > 0.4$
- MW goal achieved for $y_o < 0.75$ ($\approx$ 0.3 mm)
  - Well beyond the design tolerance of 0.01 mm

Electron Beam Shift $y_o = 0.6$



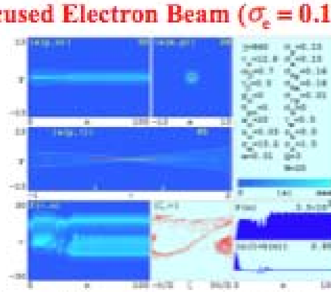
- Electron beam shift causes optical mode $|a(y,\tau)|$ to tilt
- Optical power P(n) reaches steady-state
- Extraction efficiency reduced from 2.5% to 1.8%

Peak Efficiency, $\hat{\eta}$ vs Electron Beam Radius, σ_e



- As σ_e is reduced by focusing the electron beam:
  - The efficiency increases from η = 2.5% to 4%
  - The energy spread increases from $\Delta\gamma/\gamma$=11% to 14%

Focused Electron Beam ($\sigma_e = 0.15$)



- Focused electron beam stays inside intense optical mode $|a(y,\tau)|$ at center of undulator (τ=0.5)
- Steady-state extraction efficiency η = 4%

Presentation at 24th International FEL Conference, Chicago, IL, September 2002

The Free Electron Laser Interaction with a Short-Rayleigh-Length Optical Mode

W. B. Colson, J. Blau, & R. L. Armstead
Physics Department, Naval Postgraduate School
Monterey, CA 93923 USA

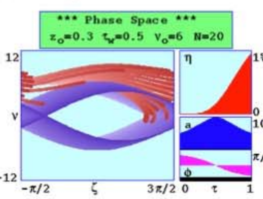
International FEL Conference, Chicago, IL, Sept 2002

ABSTRACT

- Short Rayleigh Length (SRL) optical mode reduces intensity on resonator mirrors
- FEL interaction altered with SRL mode
- SRL intensifies interaction at mode focus
  - rapidly changing optical amplitude and phase
- SRL accelerates bunching and energy extraction
- New phase space pictures illustrate interaction characteristics $\Rightarrow$ good efficiency

FEL Phase Space: Typical Rayleigh Length z_0=0.3

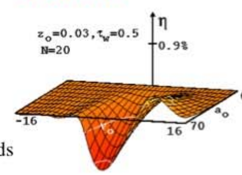
- conventional FEL values
- shows electron bunching
- modest field value a_0=10
- optimum η at ν_0=6
- FEL begins trapping
- τ=0$\rightarrow$1 along undulator
- evolution: $a(\tau)$, $\phi(\tau)$, & efficiency $\eta(\tau)$ shown



- evolving electrons become more brown as τ=0$\rightarrow$1
- evolving separatrix becomes more blue as τ=0$\rightarrow$1

Short Rayleigh Length Efficiency Map $\eta(a_0,\nu_0)$

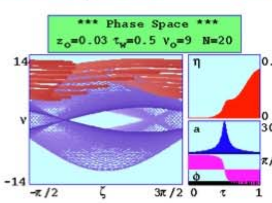
- plot final FEL efficiency $\eta = \langle \nu_0 - \nu(1) \rangle / 4\pi N$
- short Rayleigh length z_0=0.03 over N=20 periods
- efficiency is reduced further, but still OK



- peak efficiency is 0.9% at ν_0=9.6 for strong field a_0=70

Short Rayleigh Length FEL Phase Space with z_0=0.03

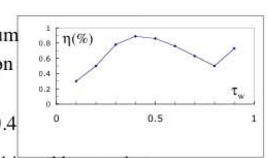
- modest field a_0=30
- optimum η at ν_0=9
- separatrix "balloons", "pulls down" electrons
- final value η =0.3%
- field $a(\tau)$ & $\phi(\tau)$ evolves rapidly at mode focus τ_w=1/2



- efficiency evolution $\eta(\tau)$ shows features of mode focus
- induced energy spread is $\Delta\nu\approx8 \Rightarrow \Delta\gamma/\gamma\approx\Delta\nu/4\pi N \approx 3\%$

Vary Mode Focus τ_w Along Undulator with z_0=0.03

- plot peak efficiency for a_0=70, z_0=0.03, ν_0 optimum
- change mode focus location from τ_w=0.1 to 0.9
- see broad peak about $\tau_w\approx$0.4



- focus at $\tau_w\approx$0.4 can be achieved by moving undulator slightly closer to resonator mirror
- for the short Rayleigh design, undulator is much smaller than the resonator mirror separation (L<<S)

STABILITY OF A HIGH POWER FEL UTILIZING A SHORT RAYLEIGH LENGTH

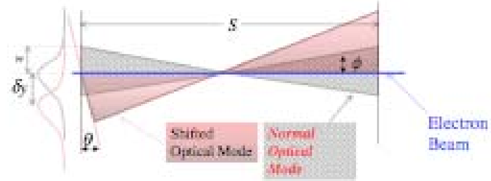
P.P. Crooker, T. Campbell, W. Ossenfort, S. Miller, J. Blau, and W.B. Colson

Naval Postgraduate School, Monterey, CA 93943

International FEL Conference, Chicago, IL, Sept 2002

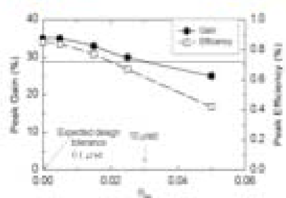
Optical Mode Tilt

- The spot center will shift δy as either mirror is tilted.
- The maximum allowable optical beam tilt ϕ_{max} occurs when the optical mode is rotated outside of the electron beam causing the spot center to shift on the order of one spot radius at the mirror ($\delta y \sim w$).



Performance Decline Due to Tilt in 100 kW FEL

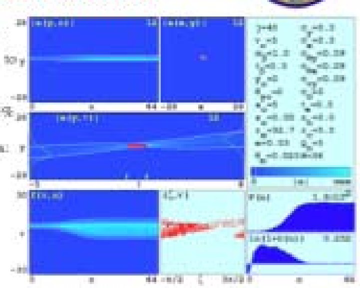
- Gain and Efficiency decrease steadily as tilt angle is increased.
- 100 kW power requires efficiency $\eta = 0.7\%$.
- performance degraded by half.



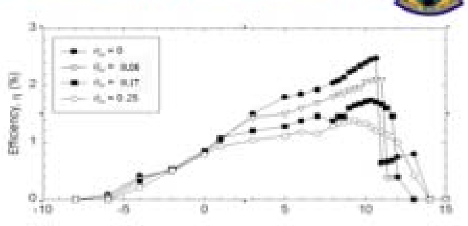
- real angles: $\theta = 0$, 2 μrad, 5 μrad, 8 μrad, 16 μrad

100 kW Steady State Mode Rotation

- Real mirror angle θ_{rot} = 8 μrad causes mode rotate ϕ_{rot} = 350 μrad.
- Final efficiency $\eta = 0.45\%$
- Dimensional conversions:
  $x = 10 \rightarrow 1$ cm
  $\Delta\tau = 1 \rightarrow 288$ cm
  $\Delta\gamma/\gamma = 3.1\%$ spread



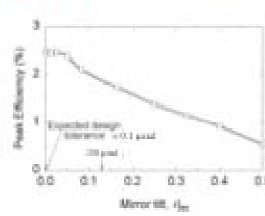
Efficiency (η) vs Phase Velocity (v_0)



- Efficiency increases up to a peak and then drops off sharply.
- As the tilt angle is increased, the optimum V_0 changes.

Performance Decline Due to Tilt in 1 MW FEL

- Gain and Efficiency decrease steadily as tilt angle is increased.
- 1 MW power requires efficiency $\eta = 0.7\%$.
- Efficiency reduction to less than 0.7% does not occur until tilt is orders of magnitude greater than expected design tolerance.



- real angles: $\theta = 0$ to 360 μrad.

Presentation at 5th Directed Energy Symposium, Monterey, CA, October 2002

SIMULATIONS OF THE PROPOSED 100 kW JEFFERSON LAB FREE ELECTRON LASER

W. Ossenfort, T. Campbell, V. Bouras, A. Kalfoutzos, J. Blau, P. P. Crooker, W. B. Colson

Physics Dept, Naval Postgraduate School, Monterey, CA

and

S. V. Benson, D. R. Douglas, H. F. Dylla, G. R. Neil, M. D. Shinn

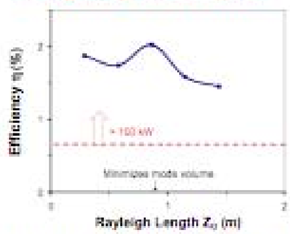
Free Electron Laser Department, Thomas Jefferson National Accelerator Facility, Newport News, VA

Directed Energy Professional Society Symposium, Monterey, CA, Oct 2002

Outline

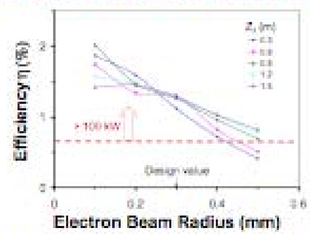
- Status of 10 kW system
- Design parameters and goals for 100 kW FEL
- Simulation results: 100 kW achievable!
- Use simulations to study various effects
  - Short Rayleigh length optical cavity
  - Electron beam focusing
  - Cavity vibrations, mirror tilt
  - Undulator tapering (linear and step)

Extraction Efficiency vs Rayleigh Length



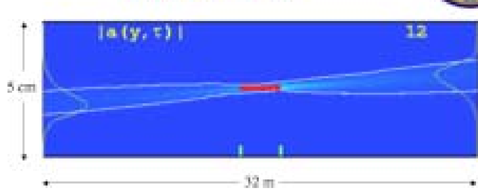
- Shorter Rayleigh length maintains good efficiency
- Similar power output, less mirror damage

Extraction Efficiency vs Electron Beam Radius



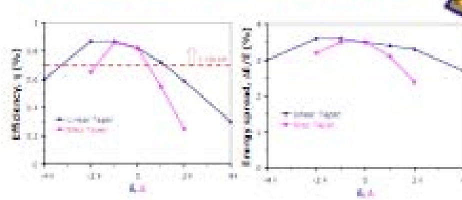
- Smaller electron beam radius improves overlap with narrow optical mode in cavity center, increasing efficiency

Mode Rotation Due to Mirror Tilt



- Mirror angle $\theta = 8$ μrad causes mode to rotate $\phi = 350$ μrad
- Steady-state optical power reduced: 180 kW → 60 kW
- Active alignment: mirrors can be held within $\theta \approx 0.1$ μrad
- Simulations show negligible power reduction for $\theta < 1$ μrad

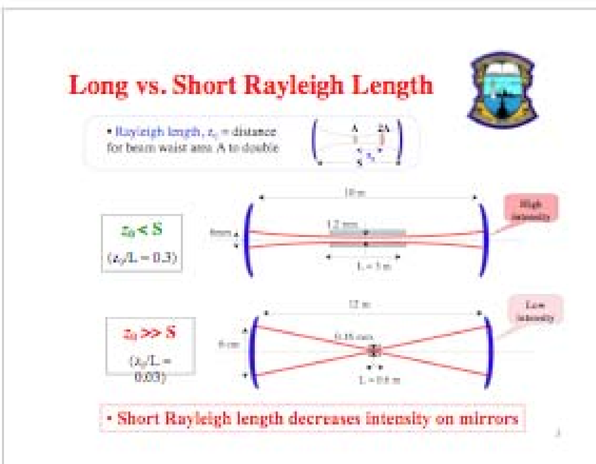
Tapered Undulator Results

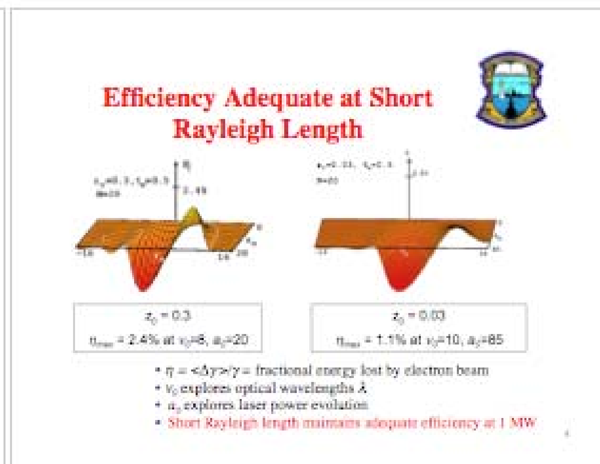


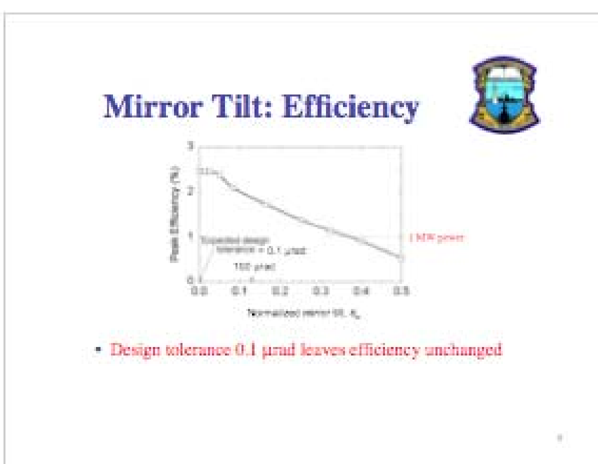
- Efficiency exceeds 100 kW requirement ($\eta > 0.7\%$)
- Energy spread within recirculation limit ($\Delta E/E < 15\%$)
- Optimum efficiency obtained with small negative taper $\delta = -2\pi$ (linear taper) or $\Delta = -\pi$ (step taper)

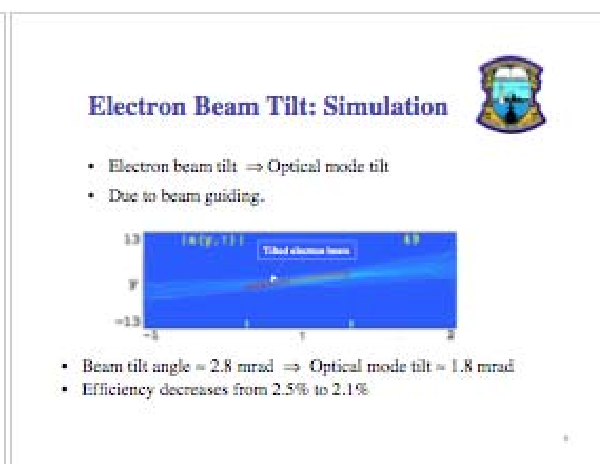

A High-Power Megawatt-Class Free-Electron Laser Using a Short Rayleigh Length
T. Campbell, W. Ossenfort, J. Blau, W.B. Colson, P.P. Crooker
Physics Dept., Naval Postgraduate School
S.V. Benson, D.R. Douglas, H.F. Dylla, G.R. Neil, M.D. Shinn
FEL Department, Thomas Jefferson National Accelerator Facility
A. Todd
Advanced Energy Systems
Directed Energy Professional Society Symposium
Monterey, CA, Oct 2002


Outline
• 1 MW specifications:
– Beam, undulator, resonator
• FEL interaction with short Rayleigh length
• Stability issues
– Mirror tilt
– Electron beam tilt
– Electron beam shift
• Electron beam focusing
• Conclusions


Long vs. Short Rayleigh Length
• Rayleigh length, z0 = distance for beam waist area A to double
z0 < S
(z0/L = 0.3)
High intensity
z0 >> S
(z0/L = 0.03)
Low intensity
• Short Rayleigh length decreases intensity on mirrors


Efficiency Adequate at Short Rayleigh Length
z0 = 0.3
ηmax = 2.4% at ν0=8, a0=20
z0 = 0.03
ηmax = 1.1% at ν0=10, a0=85
• η = <Δγ>/γ = fractional energy lost by electron beam
• ν0 explores optical wavelengths λ
• a0 explores laser power evolution
• Short Rayleigh length maintains adequate efficiency at 1 MW


Mirror Tilt: Efficiency
Peak Efficiency (%)
Normalized mirror tilt
1 MW power
• Design tolerance 0.1 μrad leaves efficiency unchanged


Electron Beam Tilt: Simulation
• Electron beam tilt ⇒ Optical mode tilt
• Due to beam guiding.
Tilted electron beam
• Beam tilt angle ≈ 2.8 mrad ⇒ Optical mode tilt ≈ 1.8 mrad
• Efficiency decreases from 2.5% to 2.1%

HIGH ENERGY LASERS FOR SHIP-DEFENSE AND MARITIME PROPAGATION

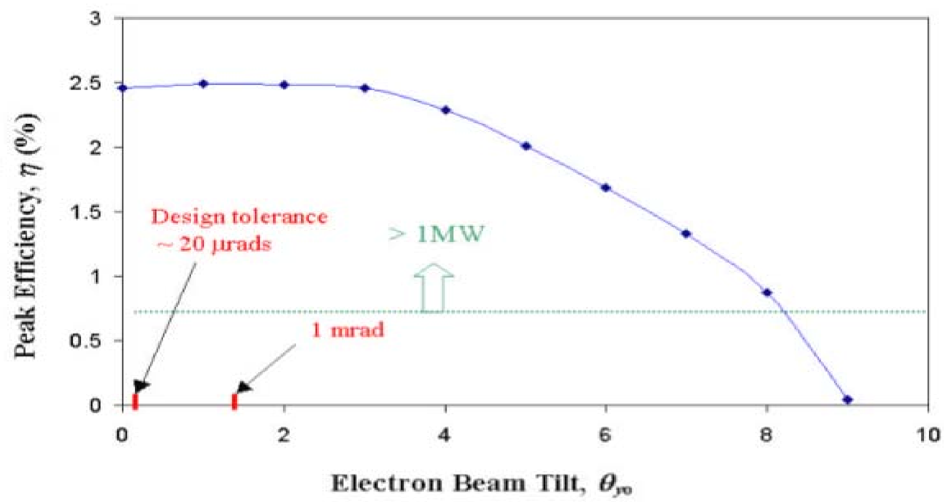
by

Vasileios Bouras

December 2002

Thesis Advisor: William B. Colson
Co-Advisor: Phillip E. Pace

High Energy Lasers (HELs) are a new class of weapons that may be of great value to the Navy in the near future. A high-power Free Electron Laser (FEL) is being designed using short Rayleigh-length resonators to increase the spot size at the mirrors and hence avoid mirror damage. Three-dimensional simulations are used to study the effects of an electron beam misalignment (electron beam tilt). This thesis shows that the proposed design is tolerant of typical electron beam misalignments. The performance of a step-tapered undulator is also studied for the 100 kW proposed upgrade of the Jefferson Laboratory FEL. The results of this research show that the gain is above the required threshold for the 100 kW design while the energy spread does not change significantly over any undulator design. The spectrum of the proposed FEL shows that most of the power is concentrated around the fundamental frequency. It is shown in this thesis that smooth FEL pulses can significantly reduce the negative effects of absorption and scattering. Recent HEL science and technology developments are discussed for both Free Electron and Solid State Lasers.



FREE ELECTRON AND SOLID STATE LASERS DEVELOPMENT FOR NAVAL DIRECTED ENERGY

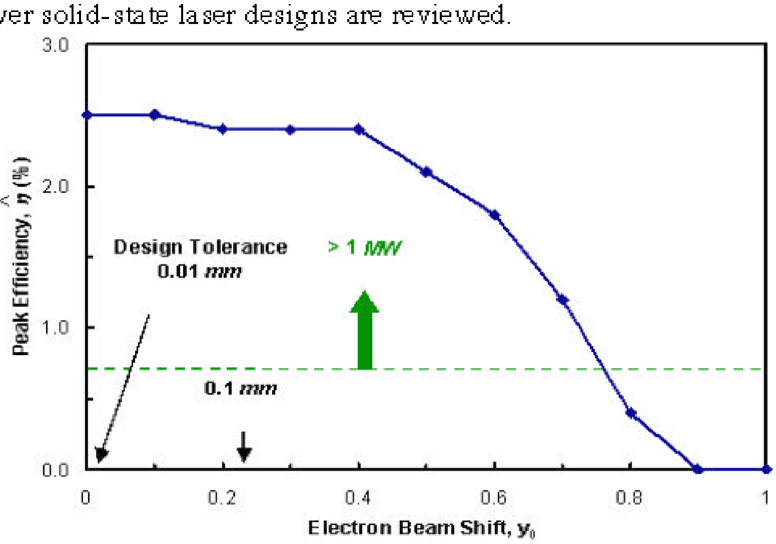
by

Aristeidis Kalfoutzos

December 2002

Advisor: William B. Colson
Co-Advisor: Phillip E. Pace

A MW level FEL is being designed with a short a Rayleigh length resonator to increase the spot size at the mirrors and to avoid mirror damage. In this thesis, it is found that it is desirable to focus the electron beam to improve the FEL extraction efficiency. Three-dimensional simulations show that the focused electron beam increases the extraction efficiency far beyond the desired value of 0.7%. It is also found in this thesis that shifting the electron beam off-axis less than 0.3 mm, the efficiency remains above the required value. The proposed FEL design uses high power, short optical pulses whose spectrum may cover many absorption lines. The absorbed laser energy can heat up the air resulting in defocusing the laser beam (thermal blooming). This thesis shows that thermal blooming is not an issue for a moderate clear atmosphere when the stagnation zone size remains less than 10 m. A transitional step for the development of a MW level FEL weapon is the proposed 100 kW upgrade of the Thomas Jefferson National Accelerator Facility's FEL. It has also been shown in this thesis that the use of a step-taper undulator slightly improves the performance of the FEL. Finally, the potential of various high average power solid-state laser designs are reviewed.



SIMULATIONS OF A SHORT RAYLEIGH LENGTH 100 kW FEL AND MIRROR STABILITY ANALYSIS

by

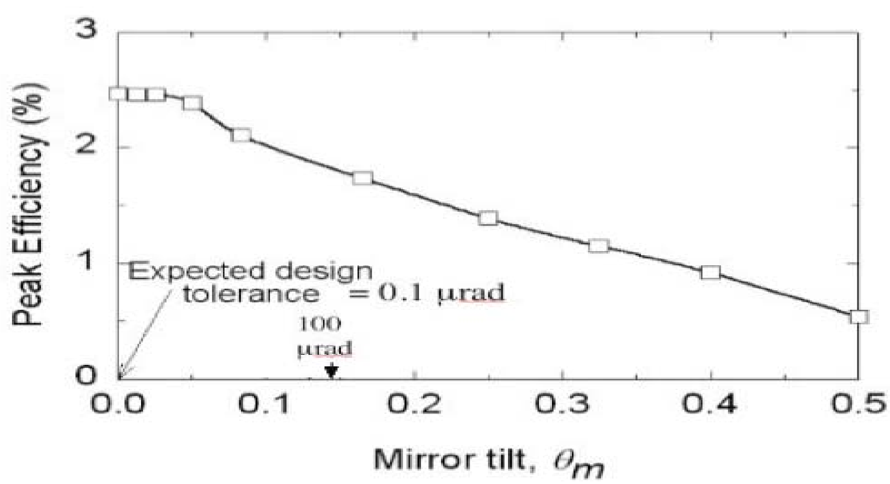
Thomas E. Campbell

December 2002

Thesis Advisor: William B. Colson
Second Reader: Robert L. Armstead

A MW class free electron laser capable of delivering energy at the speed of light can improve ASCM defensive capability for Navy ships. Many design challenges must be overcome to make such a weapon possible. One such challenge is to maintain the power density on laser cavity mirrors at acceptable levels. The use of a short Rayleigh length to increase beam spot size at the mirror is studied as a possible solution to this problem. In this thesis, it is shown that by using a short Rayleigh length FEL, power densities at the mirrors are significantly reduced without causing a noticeable reduction in performance.

For a short Rayleigh length FEL, the resonator cavity is sensitive to misalignment and vibration. The effect of mirror tilt due to vibrations is explored and the results show that as mirror tilt increases, FEL efficiency does decreases. However, a mirror tilt several orders of magnitude greater than currently achievable active alignment tolerances is required before the FEL efficiency is noticeably affected. In this thesis, it is shown that mirror tilt within achievable tolerance limits will not adversely affect the performance of a FEL.



MEGAWATT CLASS FREE ELECTRON LASERS FOR NAVAL APPLICATION – SHORT RAYLEIGH LENGTH AND STABILITY ANALYSIS

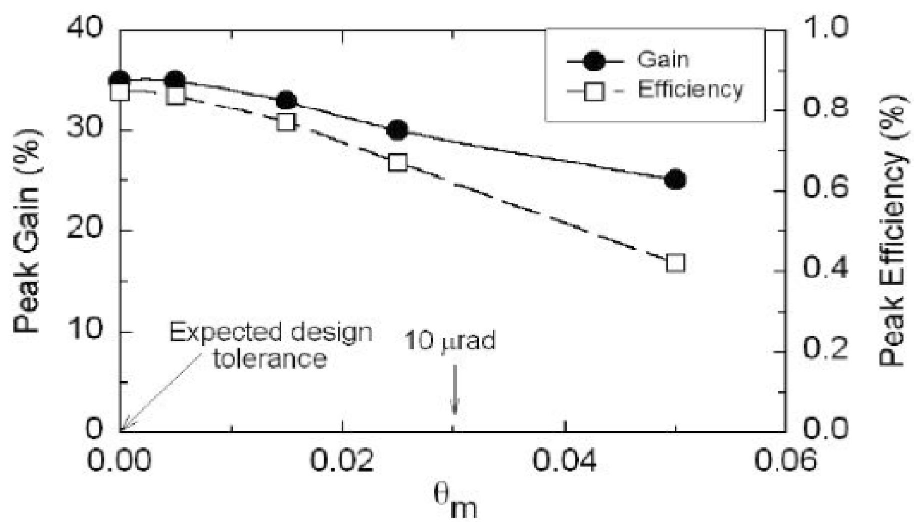
by

William J. Ossenfort Jr

December 2002

Thesis Advisor: William B. Colson
Second Reader: Robert L. Armstead

The free electron laser (FEL) is theoretically capable of scaling up to a MW class laser for naval point defense. At such high power levels, the FEL's optics could be damaged. An FEL operating with a short Rayleigh length reduces intensity at the mirrors; however, the performance of short Rayleigh length FELs is unknown. This thesis presents simulations of Thomas Jefferson Laboratories' proposed 100 kW FEL operating with a short Rayleigh length, and of a proposed 1 MW FEL undergoing shipboard induced mirror vibrations. In the 100 kW FEL, Rayleigh lengths of 0.1L to 0.5L (where L is the undulator length) were simulated. Weak field gain increases as Rayleigh length decreases, indicating that short Rayleigh length FELs will start from spontaneous emissions. Final FEL efficiency also increases as Rayleigh length decreases, with the exception of a spike at the typical Rayleigh length design value of 0.3L. For the 1 MW FEL system, the high operating current acts to stabilize the optical mode against vibrations that result in mirror tilts of 0 to 400 microradians, where final output power was reduced 80%. When used in conjunction with an active mirror alignment system, output power of the 1 MW FEL is unaffected.



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Nuclear Instruments and Methods in Physics Research A 507 (2003) 44–47

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Simulations of high-power free electron lasers with strongly focused electron and optical beams

J. Blau, V. Bouras, A. Kalfoutzos, G. Allgaier, T. Fontana, P.P. Crooker, W.B. Colson*

Physics Department, Naval Postgraduate School, 833 Dyer Road, Monterey, CA 93943, USA

Abstract

A high-power free electron laser (FEL) is being designed in collaboration with Jefferson Laboratory, University of Maryland and Advanced Energy Systems, using short Rayleigh-length resonators to increase the spot size at the mirrors and hence avoid mirror damage. A short Rayleigh length implies a very small optical mode waist in the center of the cavity. It may be desirable to strongly focus the electron beam as well, to improve overlap with the intense optical fields in the interaction region. Three-dimensional simulations are used to study the effects of varying the electron beam radius and angular spread to enhance FEL gain and efficiency. The effects of off-axis shifting and tilting of the electron beam are also studied.

PACS: 41.60Cr

Keywords: Free electron laser; High power laser

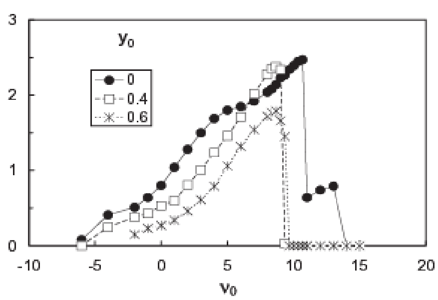

Fig. 1. Single-pass extraction efficiency η versus initial phase velocity ν_0, for three values of normalized electron beam offset y_0.

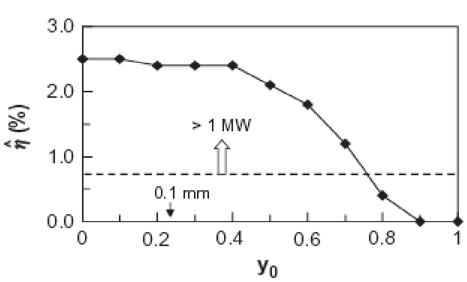

Fig. 2. Peak single-pass extraction efficiency $\hat{\eta}$ versus normalized electron beam offset y_0.

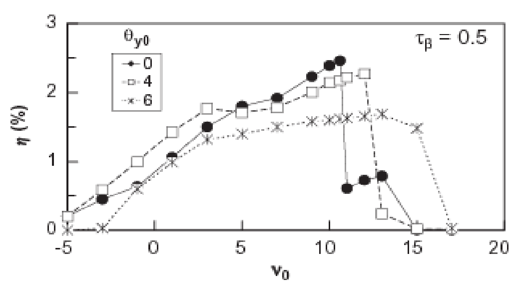

Fig. 3. Single-pass extraction efficiency η versus initial phase velocity ν_0, for three values of normalized electron beam tilt θ_{y0} through the center of the undulator ($\tau_\beta = 0.5$).

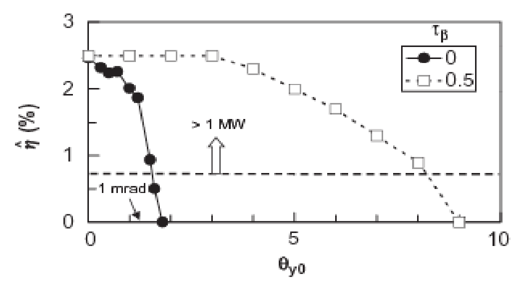

Fig. 4. Peak single-pass extraction efficiency $\hat{\eta}$ versus normalized electron beam tilt θ_{y0} at the beginning of the undulator ($\tau_\beta = 0$) and through the center of the undulator ($\tau_\beta = 0.5$).

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The free electron laser interaction with a short-Rayleigh-length optical mode

W.B. Colson*, J. Blau, R.L. Armstead

Physics Department, Naval Postgraduate School, 833 Dyer Road, Monterey, CA 93943, USA

Abstract

High-power, short-wavelength free electron lasers (FELs) can make use of a short-Rayleigh-length (SRL) optical mode in order to reduce the intensity on resonator mirrors. The conventional FEL interaction attempts to optimize the coupling between the electron beam and optical mode by minimizing the optical mode volume around the electron beam. In contrast, the SRL FEL focuses optical power in a small region of the undulator, which accelerates the electron bunching process. As a result, the fundamental FEL interaction is significantly altered with a rapidly changing optical field and phase along the undulator. Advantages and disadvantages of FELs designed with an SRL optical mode are discussed.

PACS: 41.60Cr

Keywords: Free electron laser; Optical resonator

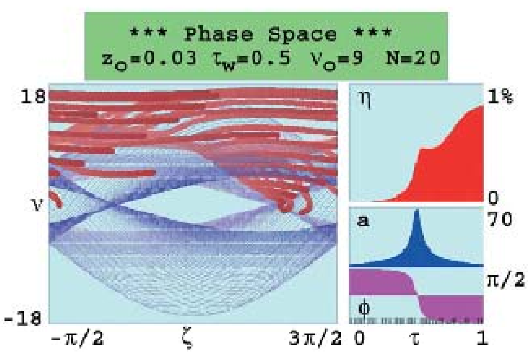

Fig. 2. The phase space evolution of the electrons and laser light for short Rayleigh length $z_0 = 0.03$.

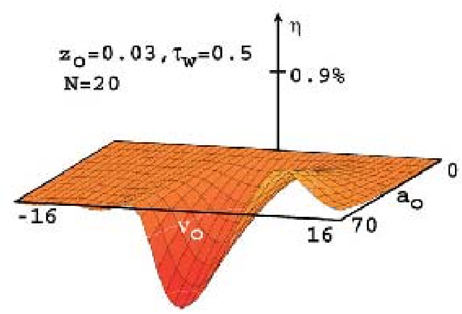

Fig. 3. For a short Rayleigh length of $z_0 = 0.03$, the efficiency map $\eta(a_0, \nu_0)$ shows a peak value of $\eta \approx 0.9\%$ occurring at $\nu_0 \approx 10$.

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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A study of the stability of a high-power free electron laser utilizing a short Rayleigh length

P.P. Crooker, T. Campbell, W. Ossenfort, S. Miller, J. Blau, W. Colson*

Physics Department, Naval Postgraduate School, Monterey, CA 93943, USA

Abstract

In order to avoid mirror damage on a high-power free electron laser (FEL), the design can utilize a short Rayleigh length optical cavity in combination with a short magnetic undulator. The short Rayleigh length increases the mode area and reduces the intensity at the mirrors, and also alters the basic FEL interaction and the stability of the laser itself. In particular, mirror misalignment may significantly affect the behavior of the cavity modes. We present simulations showing the effect of mirror tilt on the performance of 100 kW and 1 MW FEL designs with short Rayleigh lengths.

PACS: 41.60Cr

Keywords: Free electron laser; High power laser

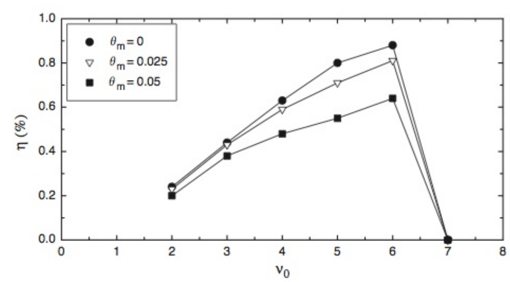


Fig. 1. Efficiency η vs. initial phase velocity ν_0 for several dimensionless mirror tilts θ_m for the 100 kW simulations. Actual mirror tilt is given by (0.332 mrad)θ_m.

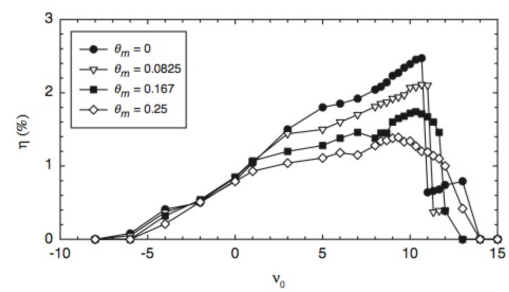


Fig. 3. Efficiency η vs. initial phase velocity ν_0 for several mirror tilts θ_m for the 1 MW simulations. Actual mirror tilt is (0.728 mrad)θ_m.

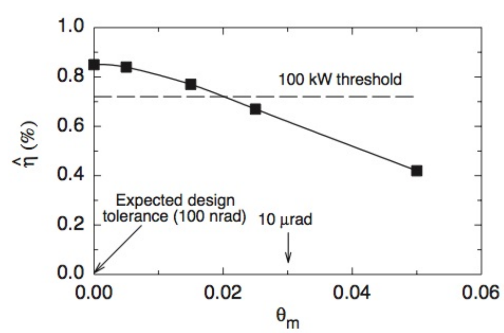


Fig. 2. Peak efficiency $\hat{\eta}$ vs. mirror tilt θ_m for the 100 kW simulation.

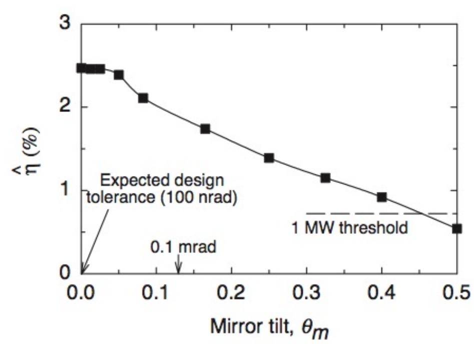
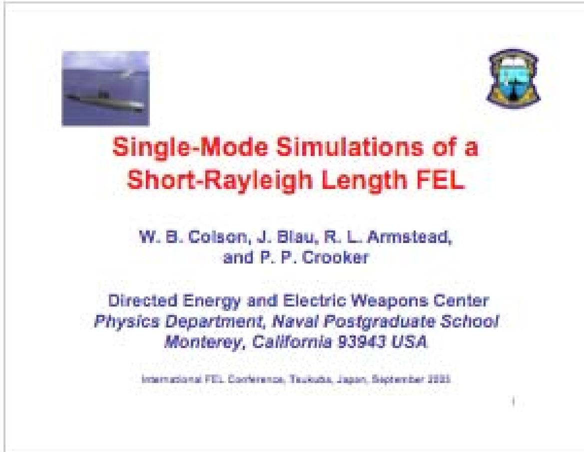
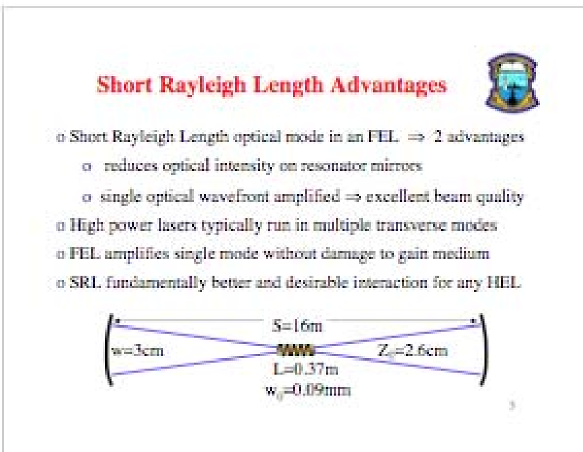
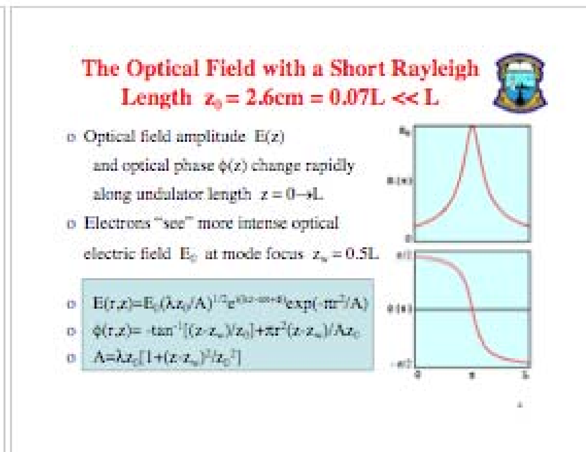


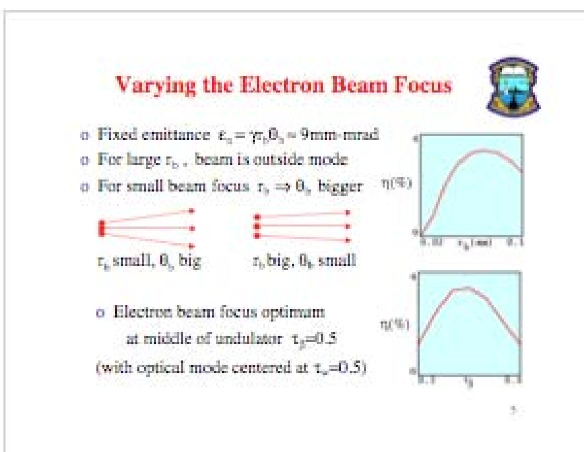
Fig. 4. Peak efficiency $\hat{\eta}$ vs. mirror tilt θ_m for the 1 MW simulation.

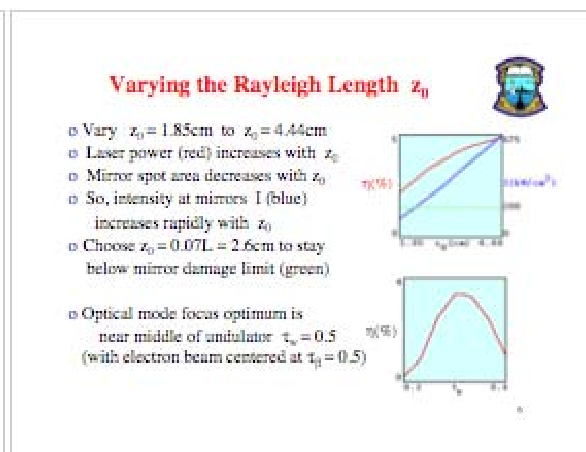

Single-Mode Simulations of a
Short-Rayleigh Length FEL
W. B. Colson, J. Blau, R. L. Armstead,
and P. P. Crooker
Directed Energy and Electric Weapons Center
Physics Department, Naval Postgraduate School
Monterey, California 93943 USA
International FEL Conference, Tsukuba, Japan, September 2003


Poster Outline
Review Short Rayleigh Length FEL Advantages
A Set of Short Rayleigh Length FEL Parameters
Introduce New, Simple FEL Simulation Method
Evaluate electron beam transverse motion
Evaluate optical mode amplitude and phase
The FEL Interaction and energy exchange
Summarize computational method
Compute Single-Pass Gain and Extraction
Analyze extraction versus E_b, q, r_b, z_0, N, Q_n

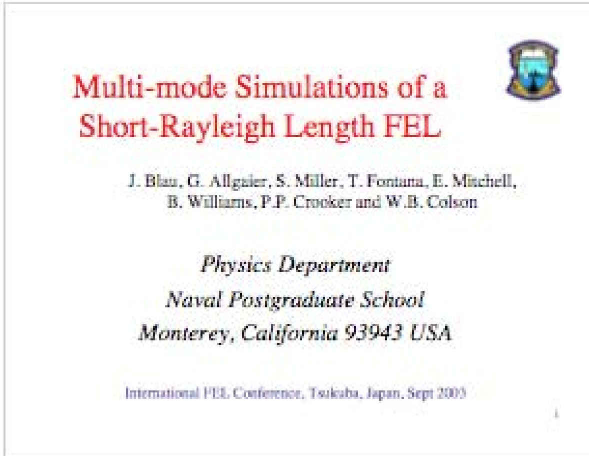

Short Rayleigh Length Advantages
Short Rayleigh Length optical mode in an FEL ⇒ 2 advantages
reduces optical intensity on resonator mirrors
single optical wavefront amplified ⇒ excellent beam quality
High power lasers typically run in multiple transverse modes
FEL amplifies single mode without damage to gain medium
SRL fundamentally better and desirable interaction for any HEL
S=16m
w=3cm
Z_0=2.6cm
L=0.37m
w_0=0.09mm

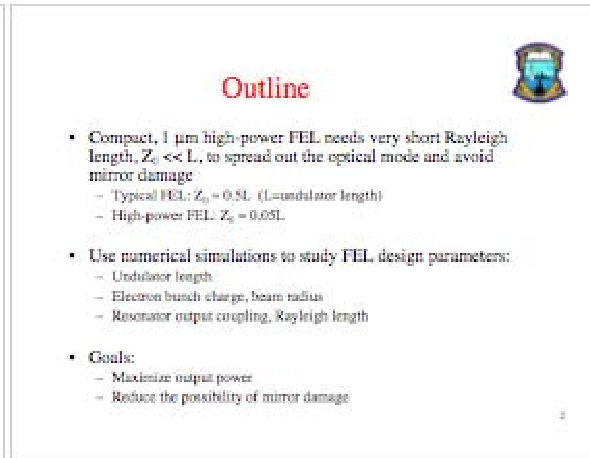

The Optical Field with a Short Rayleigh Length z_0 = 2.6cm = 0.07L << L
Optical field amplitude E(z)
and optical phase φ(z) change rapidly
along undulator length z = 0→L
Electrons "see" more intense optical
electric field E_0 at mode focus z_w = 0.5L
$E(r,z)=E_0(\lambda z_0/A)^{1/2}e^{i(kz-\omega t+\phi)}\exp(-\pi r^2/A)$
$\phi(r,z)=-\tan^{-1}[(z-z_w)/z_0]+\pi r^2(z-z_w)/Az_0$
$A=\lambda z_0[1+(z-z_w)^2/z_0^2]$

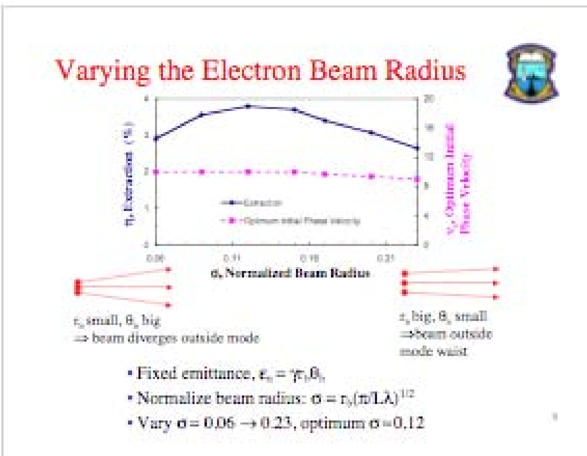

Varying the Electron Beam Focus
Fixed emittance $\varepsilon_n = \gamma r_b\theta_b \approx$ 9mm-mrad
For large r_b, beam is outside mode
For small beam focus $r_b \Rightarrow \theta_b$ bigger
r_b small, θ_b big
r_b big, θ_b small
Electron beam focus optimum
at middle of undulator τ_β=0.5
(with optical mode centered at τ_w=0.5)
η(%)
η(%)

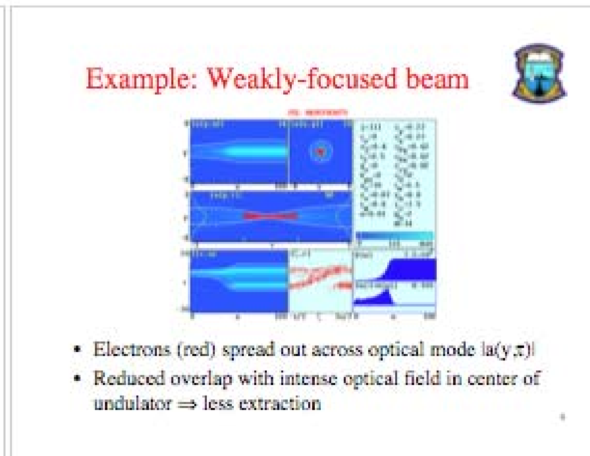

Varying the Rayleigh Length z_0
Vary z_0 = 1.85cm to z_0 = 4.44cm
Laser power (red) increases with z_0
Mirror spot area decreases with z_0
So, intensity at mirrors I (blue)
increases rapidly with z_0
Choose z_0 = 0.07L = 2.6cm to stay
below mirror damage limit (green)
Optical mode focus optimum is
near middle of undulator τ_w = 0.5
(with electron beam centered at τ_β = 0.5)
η(%)
η(%)

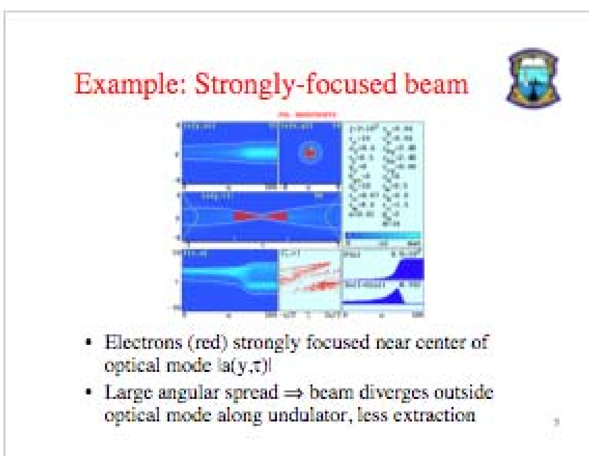
Presentation at 25th International FEL Conference, Tsukuba, Japan, September 2003

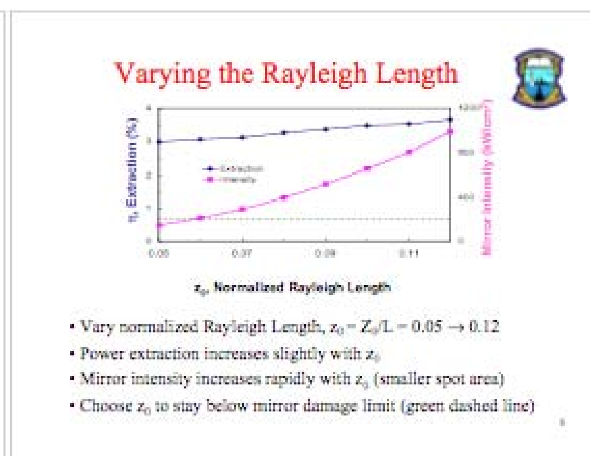












INTEGRATION OF THE FREE ELECTRON LASER, RAILGUN AND ELECTROMAGNETIC AIRCRAFT LAUNCH SYSTEM ON A NAVAL SURFACE PLATFORM

by

Seth A. Miller

September 2003

Thesis Advisor: William B. Colson
Second Reader: Robert L. Armstead

The objective of this thesis is to study the feasibility of sharing energy generation, storage and cooling systems between the Free Electron Laser (FEL), railgun and Electromagnetic Aircraft Launch System (EMALS) on all-electric ships. This thesis outlines the basic components and the theory of operation of the FEL, railgun and EMALS. A discussion of energy requirements is also provided in order to provide a basis for comparison between a shared energy storage device and the individual power supplies currently under development. A systems engineering study is then conducted to select the best type of power supply for use as a shared energy source for the FEL, railgun and EMALS. Based on the tradeoffs and assumed operational requirements of a naval surface platform, a flywheel energy storage device is suggested as the optimal choice when comparing batteries, superconducting magnetic energy storage (SMES), capacitors and flywheels as potential energy storage mechanisms. A brief discussion on the possibility of sharing cooling components between these systems and the Integrated Power System (IPS) is also provided. The remainder of this thesis focuses on a possible implementation of these devices in a shipboard environment using a ship design, an expeditionary warfare ship named the SEA FORCE, that was completed by students at the Naval Postgraduate School in the Total Ship Systems Engineering Program.

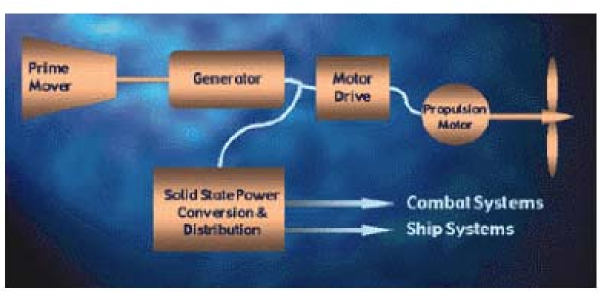
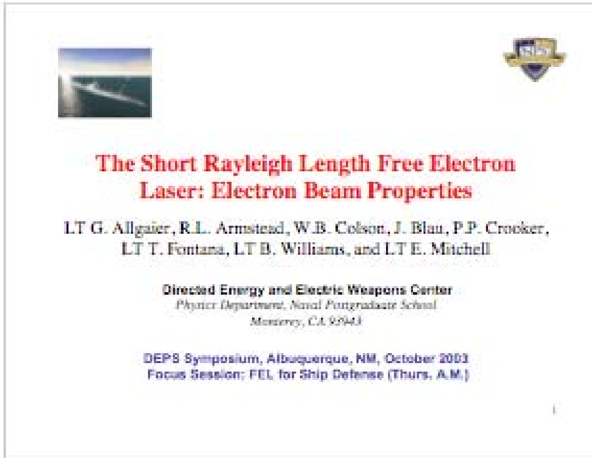
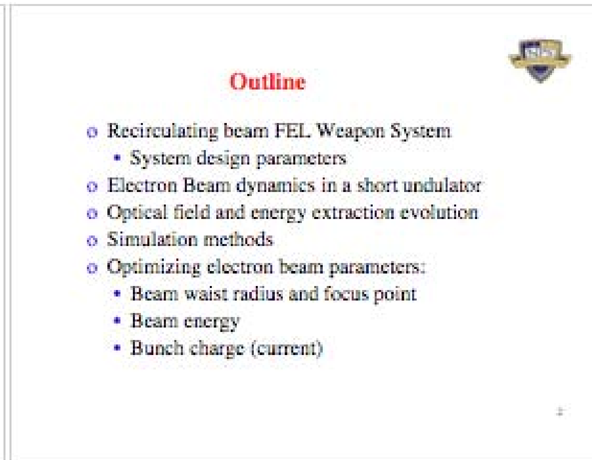
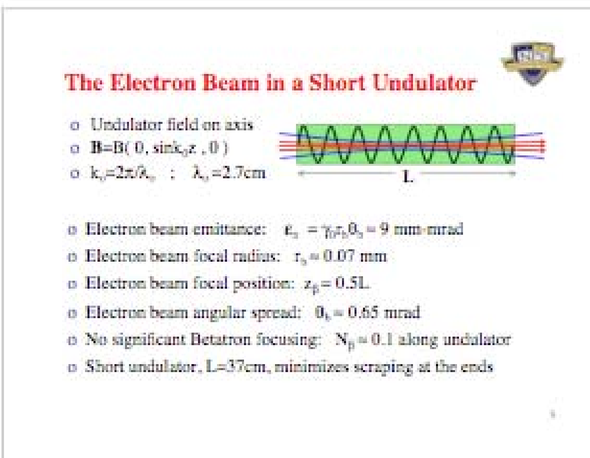


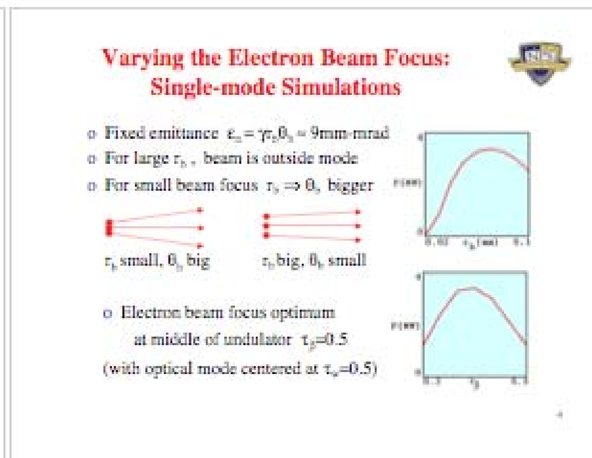
Figure 3. Integrated Power System envisioned for next generation ships.

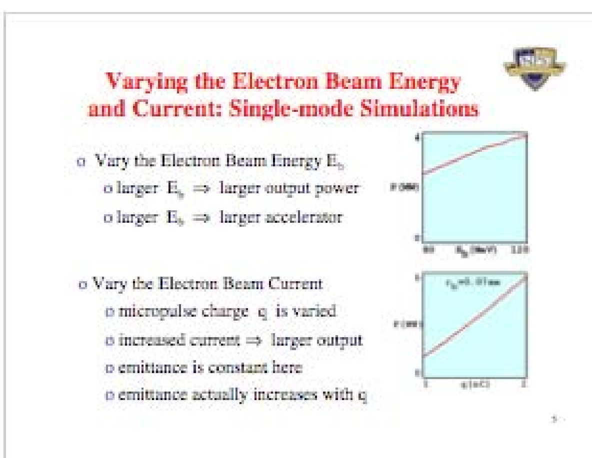
Presentation at 6th Directed Energy Symposium, Albuquerque, NM, October 2003

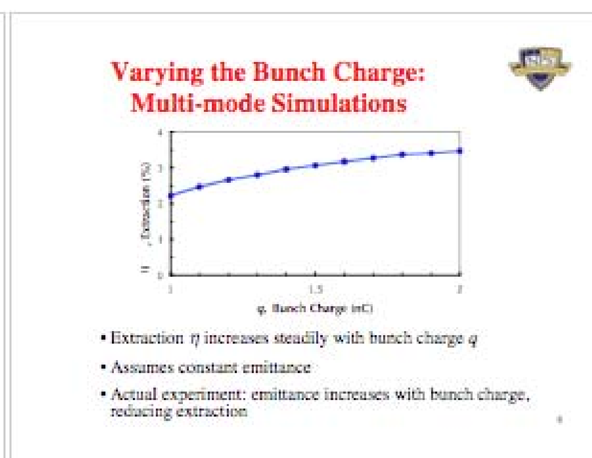




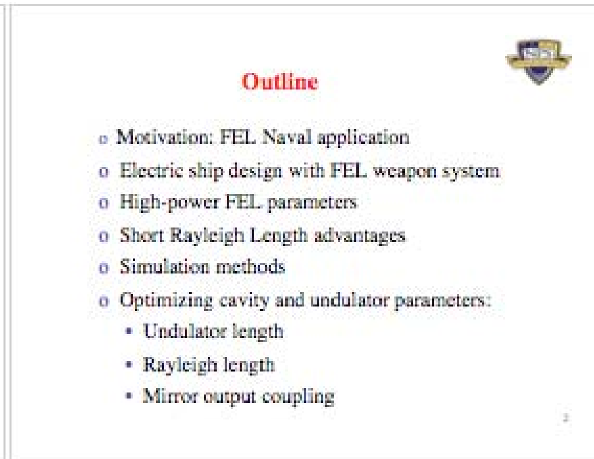


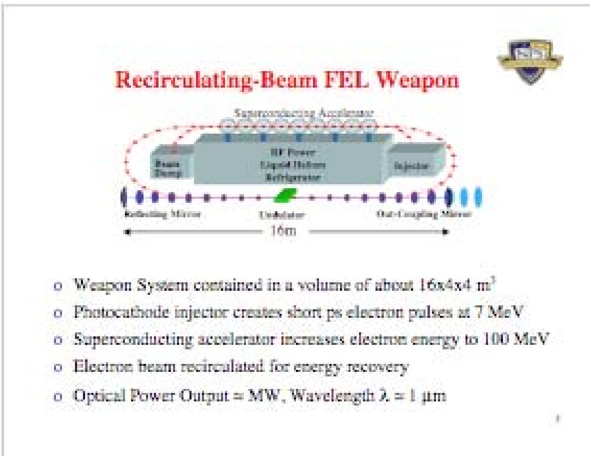


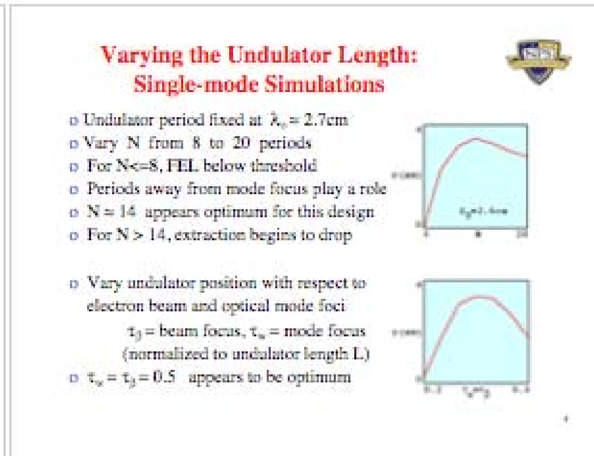


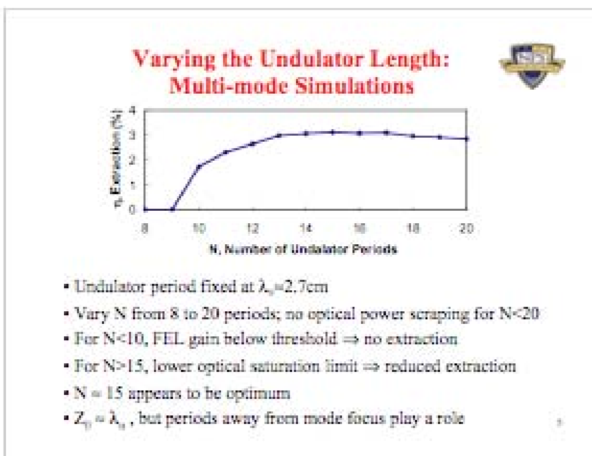


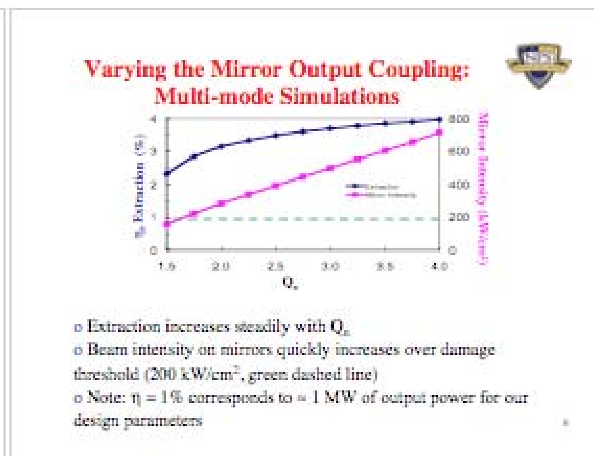
Presentation at 6th Directed Energy Symposium, Albuquerque, NM, October 2003











THE SHIBOARD EMPLOYMENT OF A FREE ELECTRON LASER WEAPON SYSTEM

by

Gregory G. Allgaier

December 2003

Thesis Advisor: William Colson
Second Reader: Robert Armstead

A megawatt (MW) class Free Electron Laser (FEL) shows promise as a new weapon for anti-ship cruise missile defense. An FEL weapon system delivers energy at the speed of light at controllable energy levels, giving the war fighter new engagement options. Considerations for this weapon system include employment, design, and stability. In order to reach a MW class laser, system parameters must be optimized and the high power optical beam must be appropriately managed.

In a high power FEL, the optical beam could heat and ultimately damage the optical cavity mirrors. One proposed solution is a short Rayleigh length design, which lowers the intensity on the mirrors, but increases sensitivity to vibrations. This thesis shows a that short Rayleigh length FEL will remain stable using current technology and can be designed to achieve a MW of power. Scenarios are then presented to explore some of the engagement options associated with this weapon system.

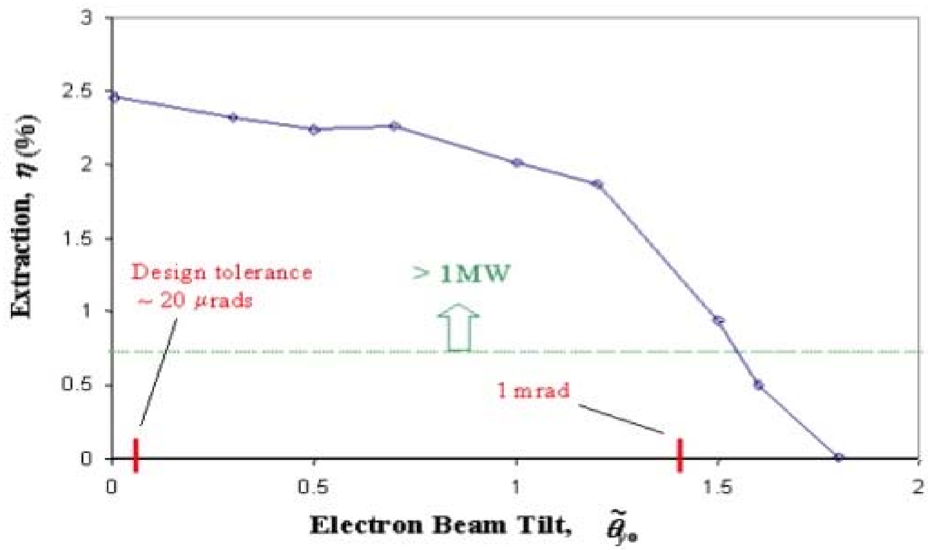


Figure 12 Extraction versus Electron Beam Tilt at the beginning of the Undulator. Performance degrades as electron beam tilt increases and sharply falls off for $\tilde{\theta}_{y0} \approx 1.2$, which is beyond the design tolerance of 20 μrad.

HIGH POWER OPTICAL CAVITY DESIGN AND CONCEPT OF OPERATIONS FOR A SHIPBOARD FREE ELECTRON LASER WEAPON SYSTEM

by

Timothy S. Fontana

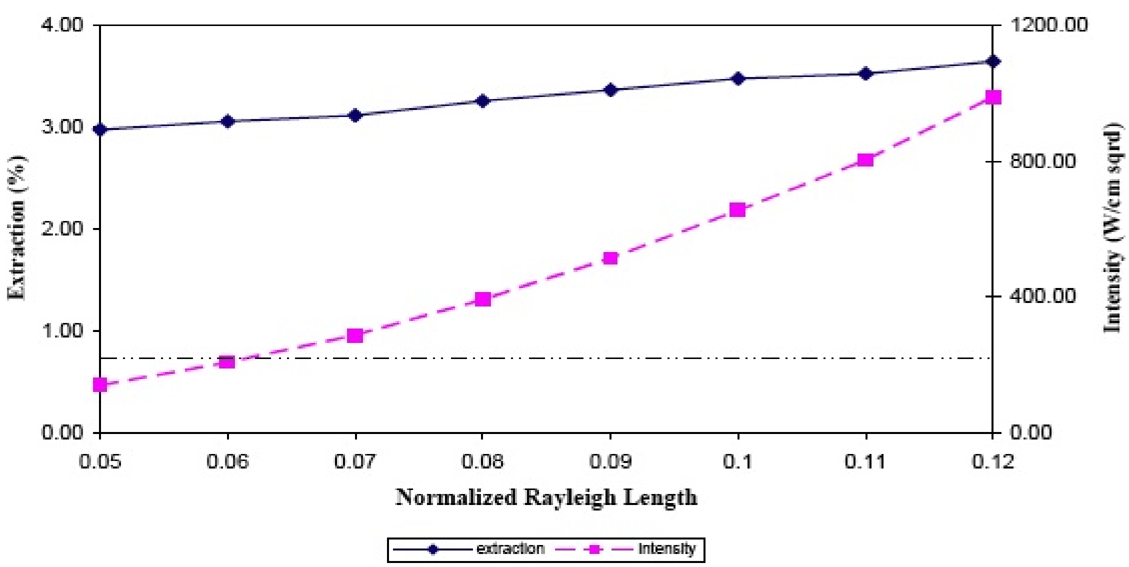
December 2003

Thesis Advisor: William B. Coulson
Second Reader: Robert L. Armstead

A megawatt (MW) class Free Electron Laser (FEL) as a point defense weapon system may lead to a revolution in anti-ship missile defense. Deep magazine, low cost per shot, proportional engagement capability, and speed of light energy delivery provide the FEL with unmatched advantages over kinetic energy weapon systems. Before and FEL is made fleet deployable, stability, system parameter optimization, and operational utility all must be taken into account.

A short Rayleigh length FEL design is being considered in order to reduce system size and mitigate resonator mirror damage. However, a short Rayleigh length can lead to vibrational sensitivities which must be studied. This thesis demonstrates that utilizing currently available technology and properly defined parameters, a short Rayleigh length FEL should be able to achieve a MW of power.

This thesis will also establish the viability of the FEL as a fleet deployable point defense weapon system through the development of a Concept of Operations (CONOPS) which draws from current naval warfare doctrine.



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Single-mode simulations of a short Rayleigh length FEL

W.B. Colson*, J. Blau, R.L. Armstead, P.P. Crooker

Physics Department, Naval Postgraduate School, Monterey, CA 93943, USA

Abstract

Free electron lasers can make use of a short Rayleigh length optical mode in order to reduce the intensity on resonator mirrors. A simulation method is used that includes the dynamics of this rapidly focusing optical mode and the macroscopic and microscopic electron evolution. The amplitude and phase of the optical fields are represented by a single Gaussian mode. The simulation runs in seconds on small laptop computers and can be used for system analysis.
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Keywords: Free electron laser; Short Rayleigh length

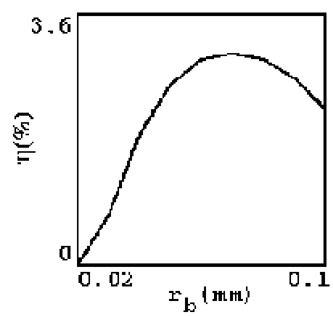


Fig. 1. The FEL extraction $\eta(r_b)$ shows optimum electron beam focal radius r_b.

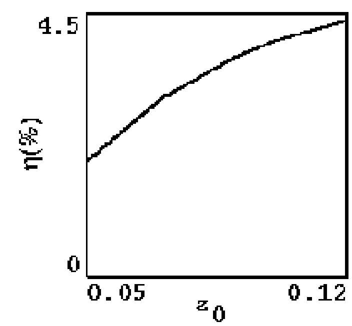


Fig. 2. The FEL extraction $\eta(z_0)$ increases monotonically with increasing Rayleigh length z_0.

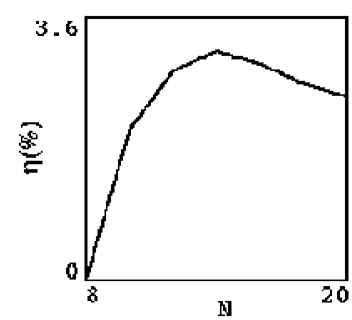


Fig. 3. The FEL extraction $\eta(N)$ shows an optimum number of undulator periods N.

MULTIPLE BEAM DIRECTORS FOR NAVAL FREE ELECTRON LASER WEAPONS

by

Ethan D. Mitchell

March 2004

Thesis Advisor: William Colson
Co-Advisor: Joseph Blau

The Free Electron Laser has the potential to become a revolutionary weapon system. Deep magazines, low cost-per-shot, pinpoint accuracy, and speed of light delivery give this developing weapon system significant advantages over conventional systems. One limiting factor in high energy laser implementation is thermal blooming, a lensing effect which is caused by the quick heating of the atmosphere, so that the laser beam does not focus on the desired spot, thereby degrading the effectiveness of the laser on target. The use of multiple beam directors focusing on a target from a single platform may mitigate thermal blooming by allowing half of the laser's energy to travel through a given volume of air, so that they only overlap very near the target. Less energy traveling through a given volume of space means less heating, and therefore lessens the effects of thermal blooming. Also, simulations of FEL's were conducted modifying parameters such as the number of undulator periods, electron beam focus, the normalized Rayleigh length, and mirror output coupling, in order to determine optimum design parameters. New parameters for the next proposed FEL were simulated to examine the effect of mirror tilt on laser power and extraction as well.

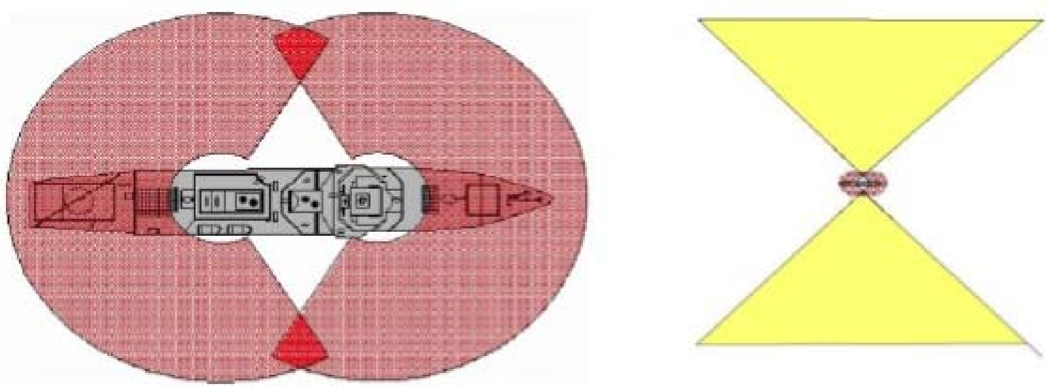


Figure 8. Firing arcs for directors placed fore and aft.

Naval Electric Weapons: The Electromagnetic Railgun and Free Electron Laser

by

Robert E. Williams

June 2004

Thesis Advisor: William B. Colson
Second Reader: Robert L. Armstead

Theory and simulations of the railgun and free electron laser are presented, as well as a suggestion for extending the railgun lifecycle. The theory, design, and analysis of an electromagnetic railgun using a numerical model are discussed. The effects of varying electrical pulse formations, rail materials and geometries are explored. The application of a metallurgical process to mitigate hypervelocity gouging in railgun rails is proposed. This concept, to delay the onset velocity of gouging by laser-peening rails surfaces, may significantly increase the velocity at which projectiles acceptably traverse the barrel and extend the useful life of rails. If successful, this process would apply to any pair of materials in sliding contact at high relative velocity, including rocket sled tracks and light gas guns barrels. The status of proof-of-concept tests at LLNL, UC Davis, and UT is covered. FEL simulations investigating the effect that electron beam focal point variations have on the optical mode, gain, and extraction within the undulator are presented.

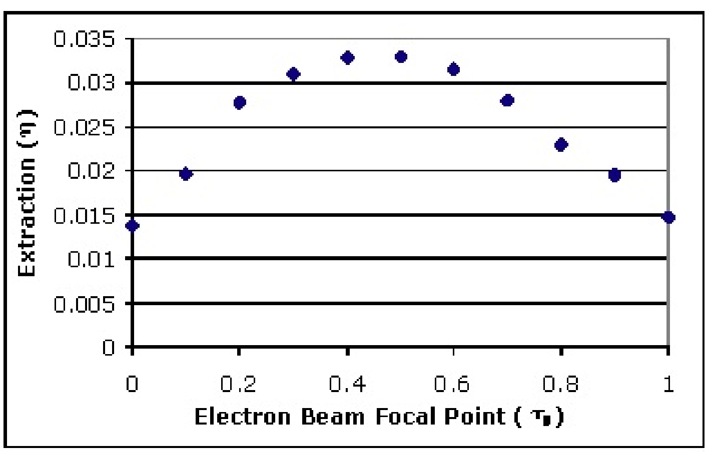


Figure 2.7. Extraction vs. Electron Beam Focal Point (strong fields)

Short Rayleigh Length Free Electron Laser Simulations In Expanding Coordinates

R.L. Armstead, J. Blau and W.B. Colson

Physics Department
Naval Postgraduate School
Monterey, CA 93943 USA

International FEL Conference, Trieste, Italy, Sept 2004

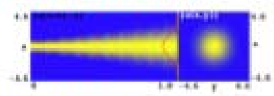
High Power FELs Use a Short Rayleigh Length Resonator

- Short Rayleigh Length (SRL) optical mode ⇒ 2 advantages
  - reduces optical intensity on resonator mirrors
  - single optical wavefront amplified ⇒ excellent beam quality

- Numerical Problem: How to "grid" w_0=0.1mm and w=30mm
- Optical field a(x,y) lives on a grid, discrete (x, y) sites →
- For $N_x=128=2^7$ at w_0=0.1mm ⇒ $N_x=65536=2^{16}$ at w=30mm
- N_x > 2048 nearly impossible

Solving For Wavefront Diffraction

- Optical Mode: z_0=0.3, $w_0=z_0^{1/2}$≈0.55 for τ=0→1 in 10 steps

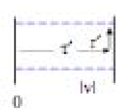


- Above mode expands to w≈1.9 at τ = 1, by amount w/w_0≈3.5
- Optical Mode: z_0=0.1, $w_0=z_0^{1/2}$≈0.32 for τ=0→1 in 10 steps

- Mode expands to w≈3.2 at τ = 1, by amount w/w_0 ≈ 10
- Problem to solve: z_0 ≈ 0.1, and τ ≈ 30 ⇒ w/w_0 ≈ 100 !!!
- **Impossible to grid both w_0 at mode waist and w at mirror !**

Coordinate Comparison

- For 0 < τ < $τ_1$, solve parabolic wave equation using linear Cartesian coordinates

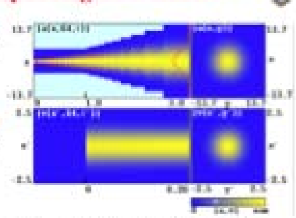


- Use expanding coordinates for τ > $τ_1$ (τ′ > 0)
- Solve for v(r′,τ′) using paraxial wave equation
- v(r′,τ′) does not diffract much

- Construct a(r,τ) from v(r′,τ′) for τ > $τ_1$
- $Δτ=τ^2Δτ′/z_0$ ⇒ time steps expand ∝ $τ^2$
- τ′ range « τ range

Solve Using Expanding Coordinates

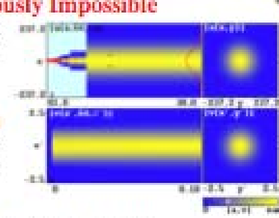
- Conventional method for τ=0→1 in 10 steps z_0=0.3, $w_0=z_0^{1/2}$≈0.55
- At τ = $τ_1$ = 1 switch to **Expanding Method** for τ=1→3 in 10 steps
- $w≈τz_0^{-1/2}$≈5.5 at τ=3
- τ′ = 0 → 0.2 only



- Optical field |a(x,τ)| shown mode center, |a(x,y)| at τ = 3
- Virtual field |v(x′,τ′)| shown mode center, |v(x′,y′)| at τ = 3
- Virtual field |v(x′,τ′)| does not expand, but does evolve
- Equal steps Δτ′ give expanding steps in τ: $Δτ = τ^2Δτ′/z_0$

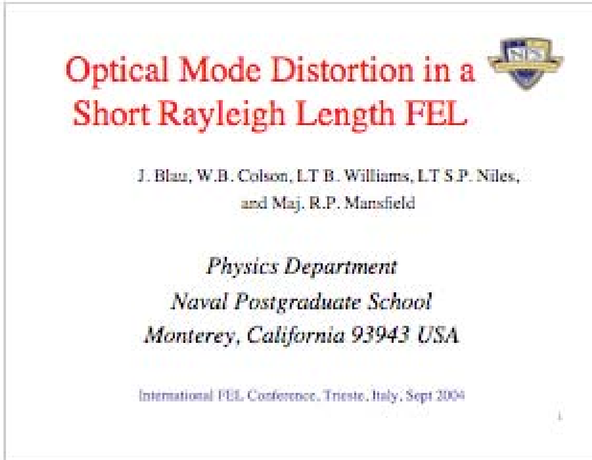
Large Range Problem, Previously Impossible

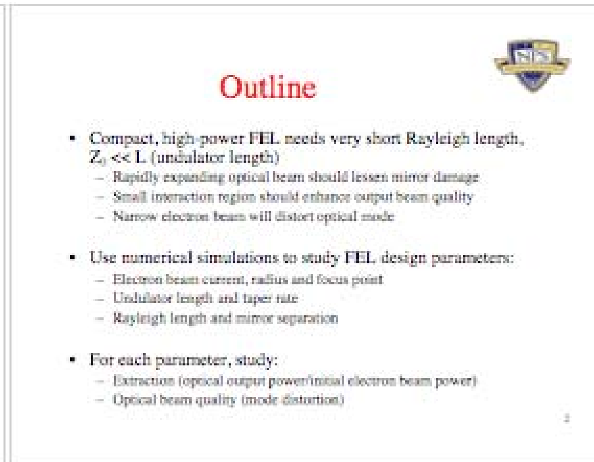
- Conventional method for τ=0→1 in 10 steps z_0=0.1, $w_0=z_0^{1/2}$≈0.32
- At τ = $τ_1$ = 1 switch to **Expanding Method** for τ=1→30 in 10 steps
- $w≈τz_0^{-1/2}$≈95 at τ=30
- τ′ = 0 → 0.1 only

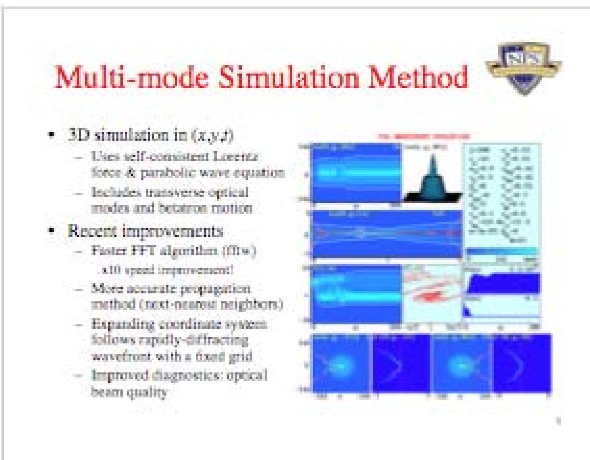


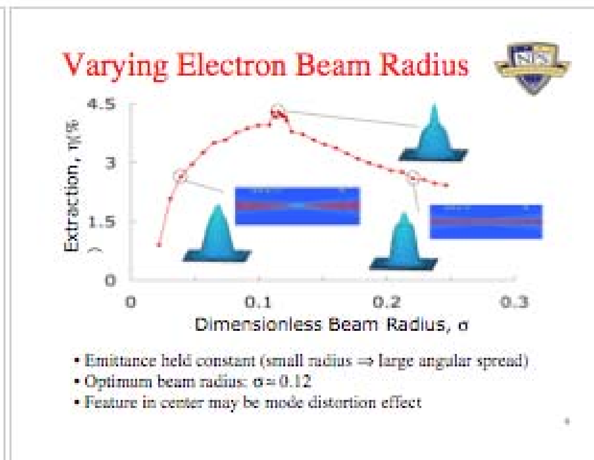
- Optical field |a(x,τ)| still Gaussian at τ=30
- Virtual field v(x′,τ′) does not experience much diffraction
- Virtual field v(x′,τ′) handles deviations from Gaussian mode
- A few equal steps Δτ′ get all the way out to τ=30

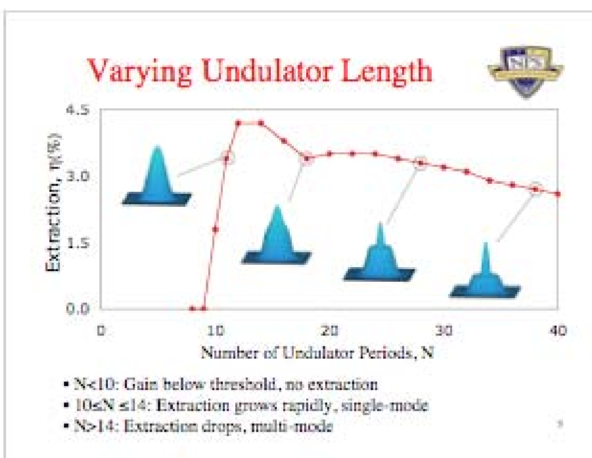
Presentation at 26th International FEL Conference, Trieste, Italy, September 2004

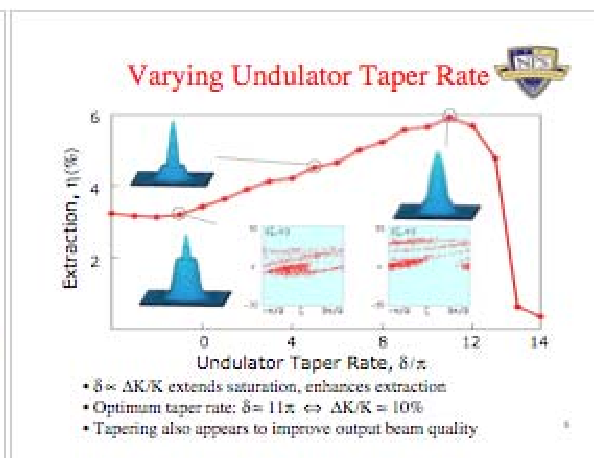




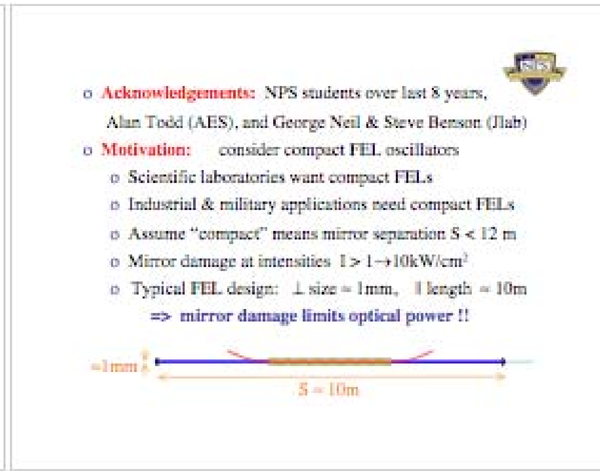


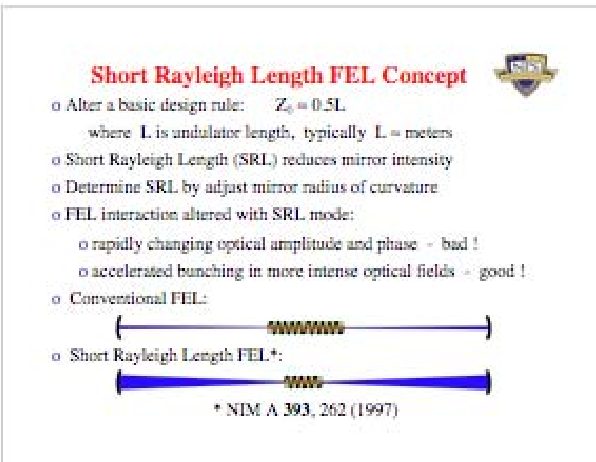


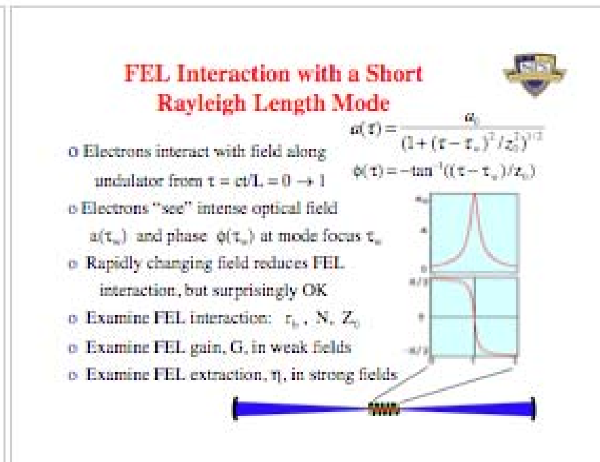


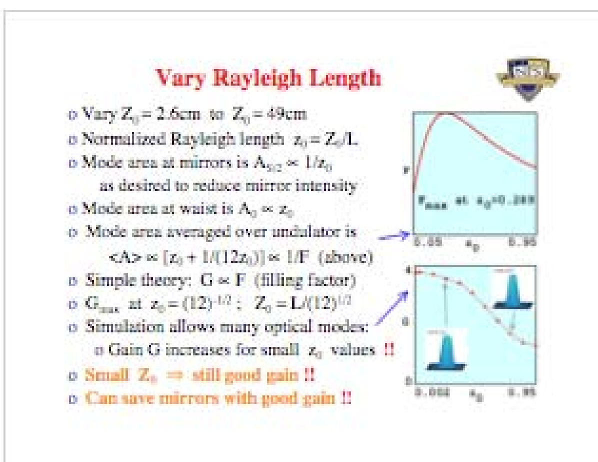


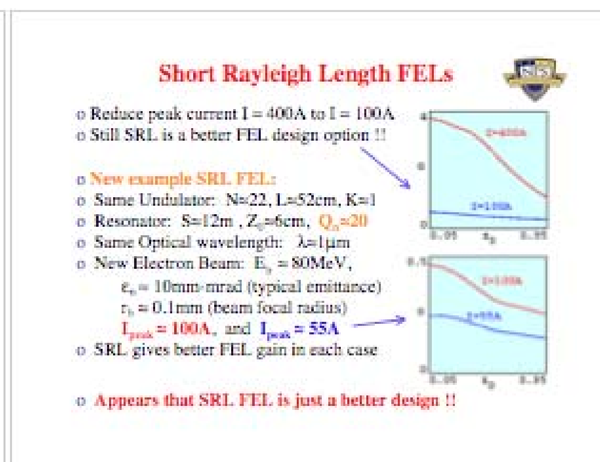

Short Rayleigh Length
Free Electron Lasers
Bill Colson,
Bob Armstead, Joe Blau, Pete Crooker
Physics Department
Naval Postgraduate School, Monterey CA 93923
FEL Conference, August 2004


Acknowledgements: NPS students over last 8 years, Alan Todd (AES), and George Neil & Steve Benson (Jlab)
Motivation: consider compact FEL oscillators
Scientific laboratories want compact FELs
Industrial & military applications need compact FELs
Assume "compact" means mirror separation S < 12 m
Mirror damage at intensities I > 1→10kW/cm²
Typical FEL design: ⊥ size ≈ 1mm, ∥ length ≈ 10m
=> mirror damage limits optical power !!
≈1mm
S ≈ 10m

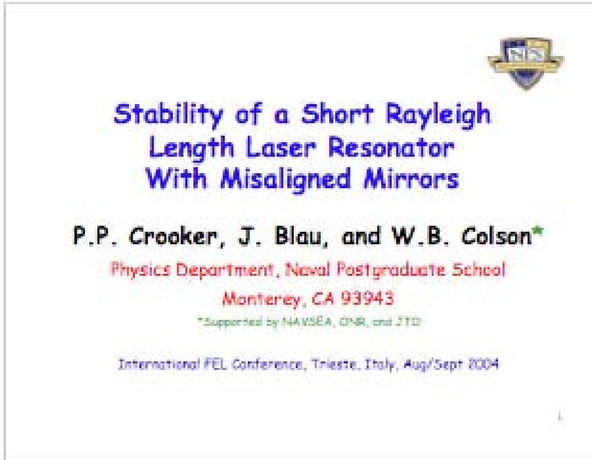

Short Rayleigh Length FEL Concept
Alter a basic design rule: Z0 ≈ 0.5L
where L is undulator length, typically L ≈ meters
Short Rayleigh Length (SRL) reduces mirror intensity
Determine SRL by adjust mirror radius of curvature
FEL interaction altered with SRL mode:
rapidly changing optical amplitude and phase → bad !
accelerated bunching in more intense optical fields → good !
Conventional FEL:
Short Rayleigh Length FEL*:
* NIM A 393, 262 (1997)

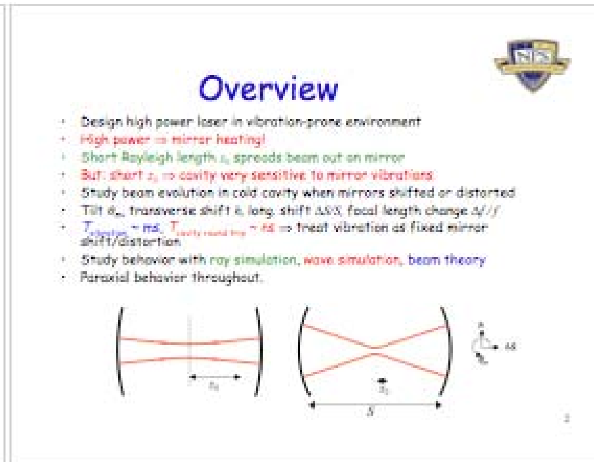

FEL Interaction with a Short Rayleigh Length Mode
Electrons interact with field along undulator from τ = ct/L = 0 → 1
Electrons "see" intense optical field a(τw) and phase φ(τw) at mode focus τw
Rapidly changing field reduces FEL interaction, but surprisingly OK
Examine FEL interaction: τb, N, Z0
Examine FEL gain, G, in weak fields
Examine FEL extraction, η, in strong fields

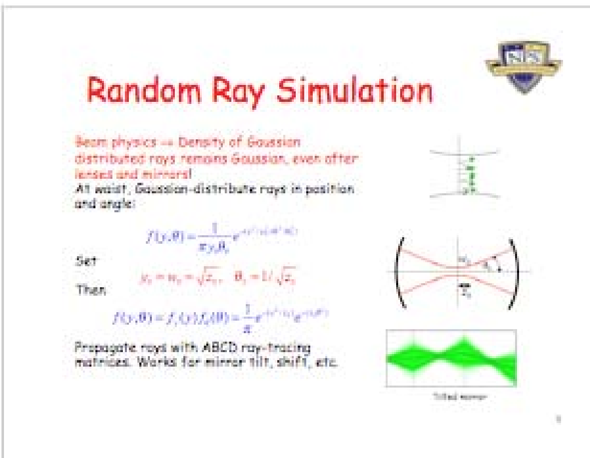

Vary Rayleigh Length
Vary Z0 = 2.6cm to Z0 = 49cm
Normalized Rayleigh length z0 = Z0/L
Mode area at mirrors is AS/2 ∝ 1/z0
as desired to reduce mirror intensity
Mode area at waist is A0 ∝ z0
Mode area averaged over undulator is
<A> ∝ [z0 + 1/(12z0)] ∝ 1/F (above)
Simple theory: G ∝ F (filling factor)
Gmax at z0 = (12)^-1/2 ; Z0 = L/(12)^1/2
Simulation allows many optical modes:
Gain G increases for small z0 values !!
Small Z0 ⇒ still good gain !!
Can save mirrors with good gain !!

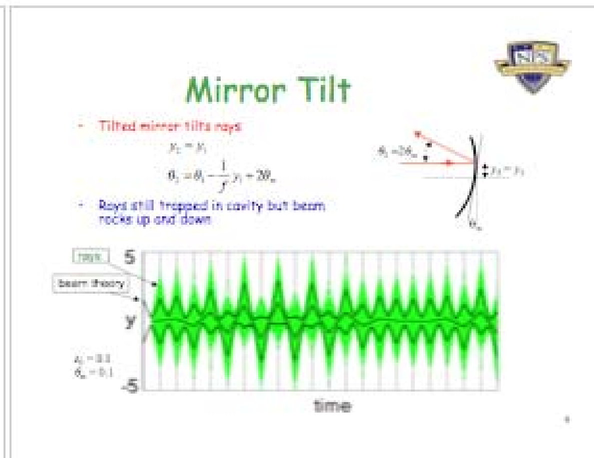

Short Rayleigh Length FELs
Reduce peak current I = 400A to I = 100A
Still SRL is a better FEL design option !!
New example SRL FEL:
Same Undulator: N=22, L=52cm, K=1
Resonator: S=12m , Z0=6cm, Qn=20
Same Optical wavelength: λ=1μm
New Electron Beam: Eb = 80MeV,
εn = 10mm-mrad (typical emittance)
rb = 0.1mm (beam focal radius)
Ipeak = 100A, and Ipeak = 55A
SRL gives better FEL gain in each case
Appears that SRL FEL is just a better design !!

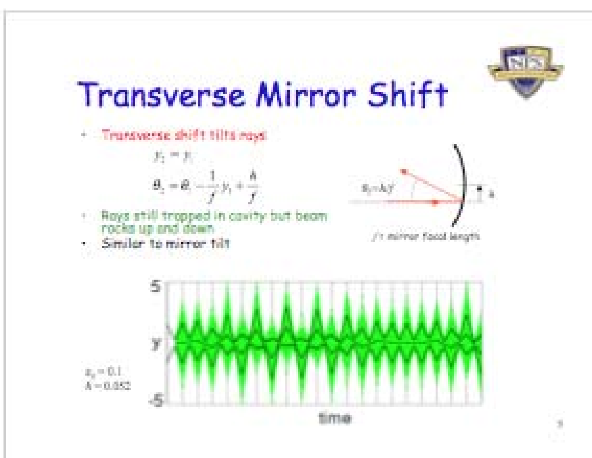
Presentation at 26th International FEL Conference, Trieste, Italy, September 2004

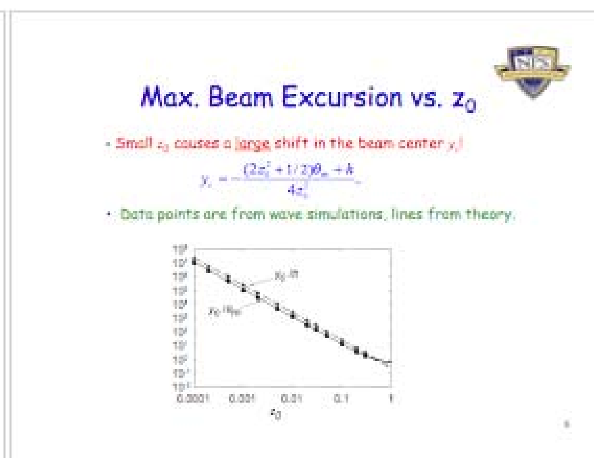












SHORT RAYLEIGH LENGTH FREE ELECTRON LASER SIMULATIONS IN EXPANDING COORDINATES

R. L. Armstead, W.B. Colson, and J. Blau
Physics Department, Naval Postgraduate School
333 Dyer Road, Monterey, CA 93943

Abstract

For compact short-Rayleigh length free electron lasers (FELs), the area of the optical beam can be thousands of times greater at the mirrors than at the beam waist. A fixed numerical grid of sufficient resolution to represent the narrow mode at the waist and the broad mode at the mirrors would be prohibitively large. To accommodate this extreme change of scale with no loss of information, we employ a coordinate system that expands with the diffracting optical mode. The simulation using the new expanding coordinates has been validated by comparison to analytical cold-cavity theory, and is now used to simulate short-Rayleigh length FELs.

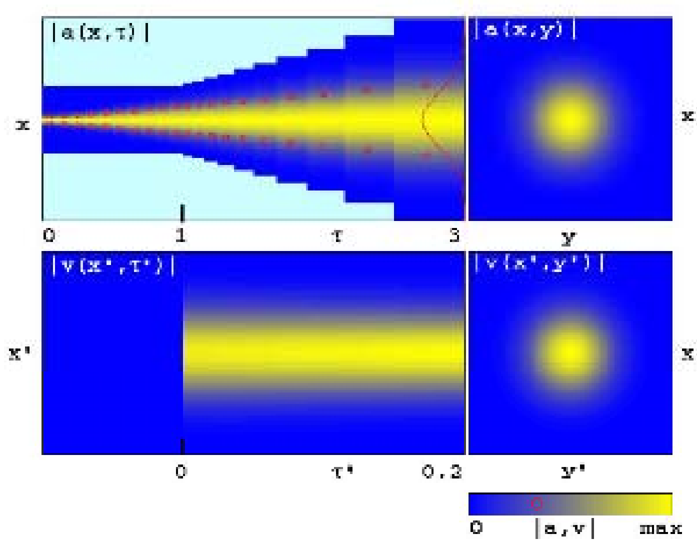


Figure 3: Free-space diffraction of a fundamental Gaussian mode in Cartesian coordinates $|a(x,\tau)|$ (top), and expanding coordinates $|v(x',\tau')|$ (bottom) for $z_0 = 0.3$, $\tau_1 = 1$, and $\tau = 0 \rightarrow 3$.

OPTICAL MODE DISTORTION IN A SHORT RAYLEIGH LENGTH FREE ELECTRON LASER

J. Blau, W.B. Colson, B.W. Williams, S.P. Niles and R.P. Mansfield
Physics Department, Naval Postgraduate School
333 Dyer Road, Monterey, CA 93943

Abstract

A short-Rayleigh length free electron laser (FEL) will operate primarily in the fundamental mode with a Gaussian profile that is narrow at the waist and broad at the mirrors. The gain medium will distort the optical wavefront and produce higher-order modes that will expand more rapidly than the fundamental. Wavefront propagation simulations are used to study optical mode distortion, as electron beam, undulator, and optical cavity parameters are varied.

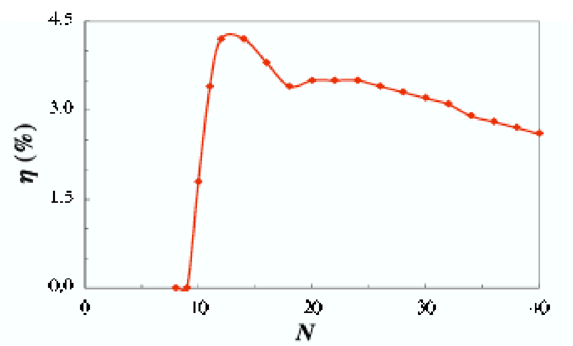


Figure 6: Simulation results for extraction η versus number of undulator periods N.

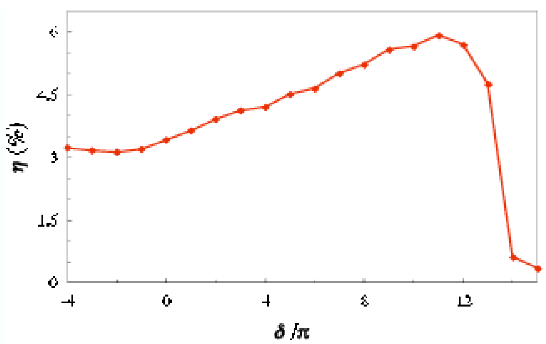


Figure 8: Simulation results for extraction η versus undulator taper strength δ.

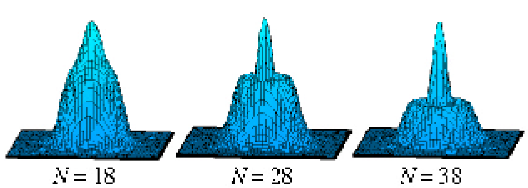


Figure 7: Optical field amplitude $|a(x,y)|$ at the output mirror for various number of undulator periods N.

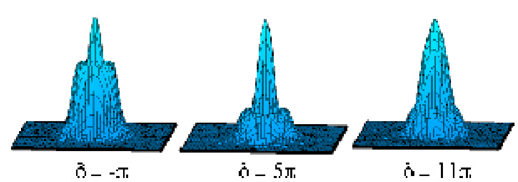


Figure 9: Optical field amplitude $|a(x,y)|$ at the output mirror for several values of undulator taper strength δ.

SHORT RAYLEIGH LENGTH FREE ELECTRON LASERS

W. B. Colson, J. Blau, R. L. Armstead, and P. P. Crooker
Physics Department, Naval Postgraduate School
Monterey, CA 93943

Abstract

Conventional free electron laser (FEL) oscillators minimize the optical mode volume around the electron beam in the undulator by making the resonator Rayleigh length about one third of the undulator length. This maximizes gain and beam-mode coupling. In compact configurations of high-power infrared FELs or moderate power UV FELs, the resulting optical intensity can damage the resonator mirrors. To increase the spot size and thereby reduce the optical intensity at the mirrors below the damage threshold, a shorter Rayleigh length can be used, but the FEL interaction is significantly altered. A new FEL interaction is described and analyzed with a Rayleigh length that is only one tenth of the undulator length, or less.

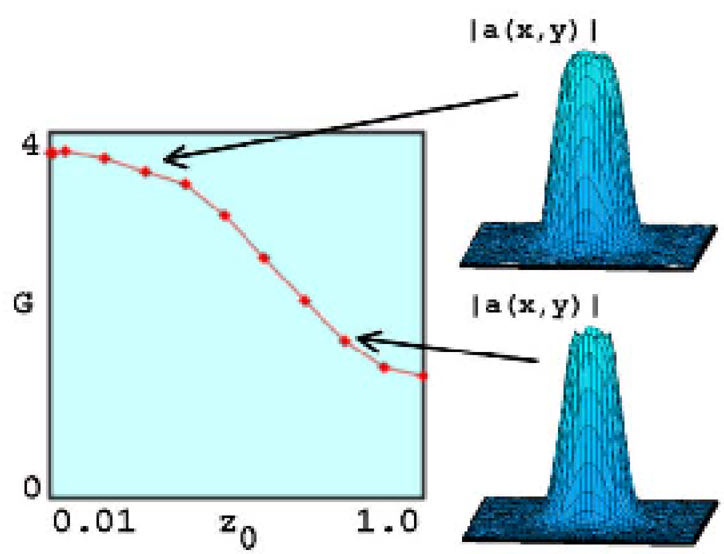


Figure 3: FEL gain as a function of Rayleigh length z_0.

STABILITY OF A SHORT RAYLEIGH RANGE LASER RESONATOR WITH MISALIGNED OR DISTORTED MIRRORS

P.P. Crooker *, J. Blau, and W.B. Colson
Naval Postgraduate School, Monterey, CA 93943 USA

Abstract

Motivated by the prospect of constructing an FEL with short Rayleigh length in a high-vibration environment, we have studied the effect of mirror vibration and distortion on the behavior of the fundamental optical mode of a cold-cavity resonator. A tilt or transverse shift of a mirror causes the optical mode to rock sinusoidally about the original resonator axis. A longitudinal mirror shift or a change in the mirror's radius of curvature causes the beam diameter at a mirror to dilate and contract with successive impacts. Results from both ray-tracing techniques and wavefront propagation simulations are in excellent agreement.

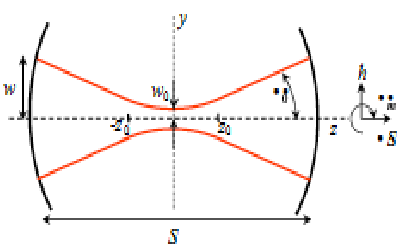


Figure 1: Resonator with Gaussian mode characterized by Rayleigh length z_0. Distortions of the right-hand mirror include tilt θ_m, transverse shift h, longitudinal shift ΔS, and focal length change Δf (not shown).

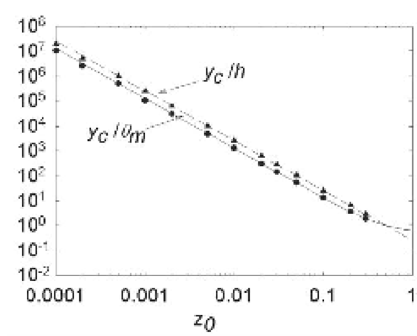


Figure 3: z_0 dependence of the maximum excursion y_c of the beam center from the original cavity axis when a mirror tilts by θ_m or undergoes transverse shift h. Tilt and shift are plotted separately. The lines are beam theory; the points are from wave simulations. For an FEL with S = 10 m and λ = 1 μm, $y_c = 10$ corresponds to 1.8 cm.

HIGH ENERGY LASER APPLICATIONS IN A SURFACE COMBATANT: TERMINAL PHASE THEATER BALLISTIC MISSILE DEFENSE, LOW ATMOSPHERE PROPAGATION, AND FREE ELECTRON LASER GAIN

by

Sean P. Niles

June 2005

Thesis Advisor: William Colson
Second Reader: Robert Armstead

The Free Electron Laser (FEL) can provide the naval surface combatant with a directed energy weapon that can be used against a large target set. Due to space constraints in a shipboard installation, an exploration is conducted to show the feasibility of short Rayleigh length FELs using a FEL simulation. Low atmosphere engagements are discussed through the modeling of a turbulence module for laser propagation in cruise missile defense applications. In particular, this thesis explores the difficulties in engaging a short/medium range theater ballistic missile (TBM) in the terminal phase as an engagement scenario in support of littoral operations using HELCoMES, developed by SAIC, as an engagement analysis tool. A concept of operations (CONOPS) for the use of a FEL as an area TBM defensive weapon is explored, using a unitary, high explosive warhead model and extrapolations to other TBM warhead types.

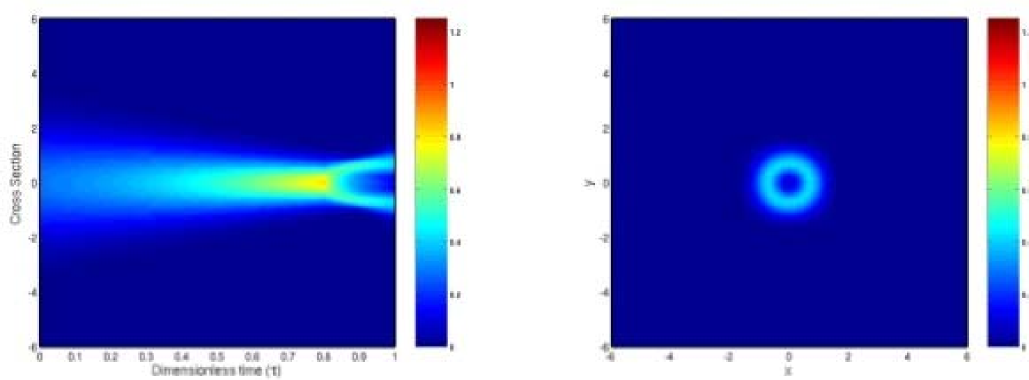


Figure 14. A propagating beam experiencing moderate thermal blooming at stagnation point $\tau_b = 0.8$ with strength $\phi_b = 0.6$. The picture to the right is a cross section of the beam at the target.

HIGH ENERGY SOLID STATE AND FREE ELECTRON LASER SYSTEMS IN TACTICAL AVIATION

by

Robb P. Mansfield

June 2005

Thesis Advisor:	William B. Colson
Second Reader:	Robert L. Armstead

A study and analysis of high energy laser (HEL) systems aboard tactical aircraft is performed. The FA-18E/F Hornet and F-35 Joint Strike Fighter (JSF), equipped with solid-state HEL systems, are the main subjects of the study. Considerations of power generation and thermal management for a fighter-sized HEL system and aero-optic effects on beam propagation from high and medium altitude platforms are examined. An overview of system capabilities details how the HEL system will be more difficult to incorporate into legacy strike aircraft, but may be feasible for future aircraft such as the JSF. Tactical flight simulations are used to study and develop potential concepts of operation (CONOPS), using realistic scenarios and threat environments. Results show that a tactical HEL will not be a stand-alone weapon in combat, but will have many potentially useful tactical applications. Another study of a high energy free electron laser (FEL) system aboard a C-130J-30 Hercules shows that such a system is feasible. Finally, a study of the FEL shows that strong field extraction can be optimized using undulator tapering.

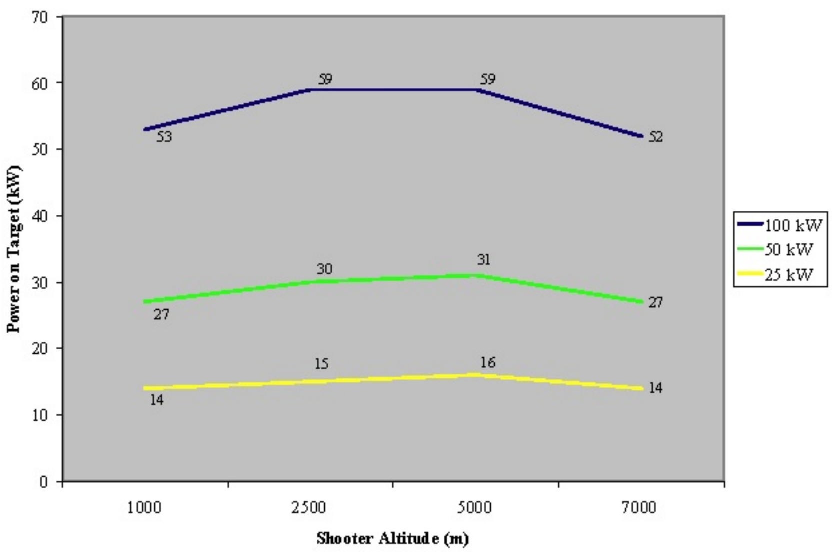
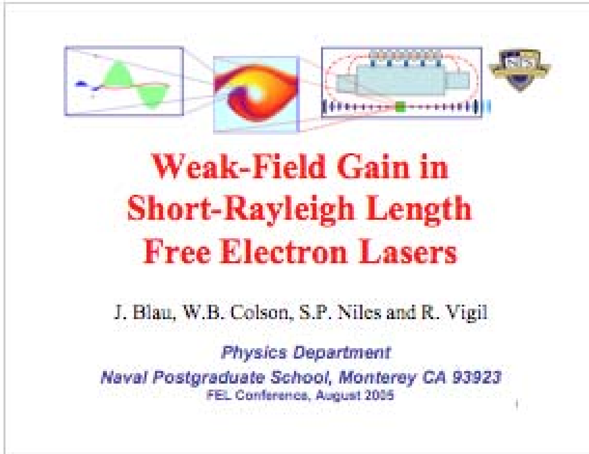
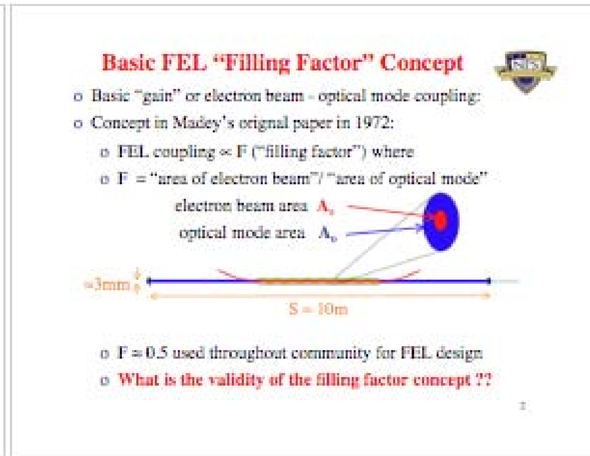


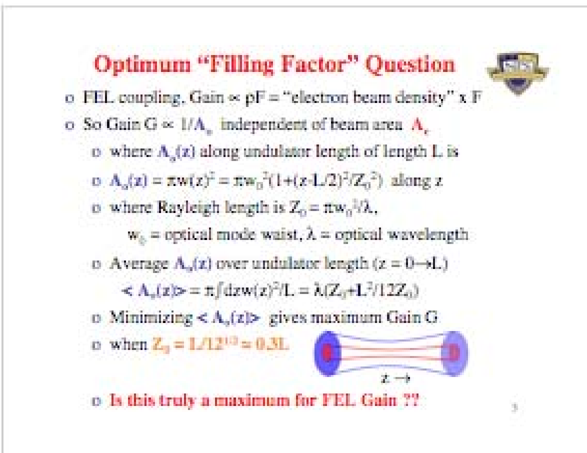
Figure 11. HEL-equipped FA-18E/F



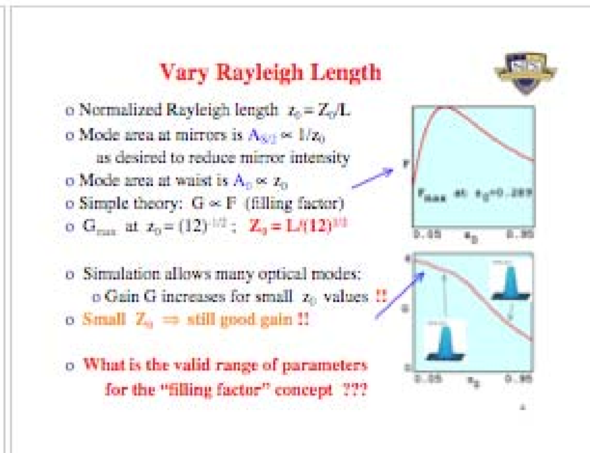
Weak-Field Gain in Short-Rayleigh Length Free Electron Lasers
J. Blau, W.B. Colson, S.P. Niles and R. Vigil
Physics Department
Naval Postgraduate School, Monterey CA 93923
FEL Conference, August 2005
1



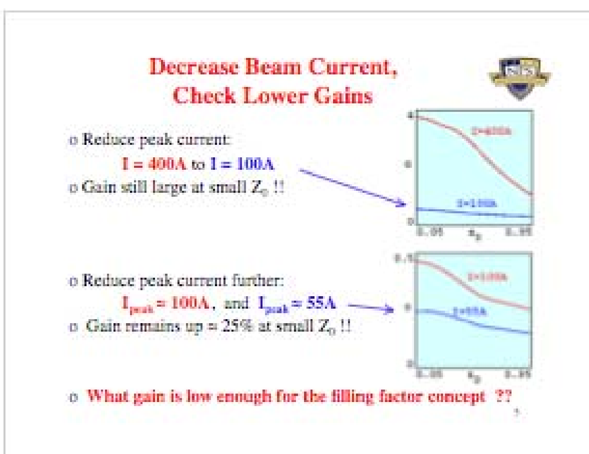
Basic FEL “Filling Factor” Concept
o Basic “gain” or electron beam - optical mode coupling:
o Concept in Madey’s orignal paper in 1972:
o FEL coupling $\propto$ F (“filling factor”) where
o F = “area of electron beam”/ “area of optical mode”
electron beam area A_e
optical mode area A_o
$\approx$3mm
S = 10m
o F $\approx$ 0.5 used throughout community for FEL design
o What is the validity of the filling factor concept ??
2



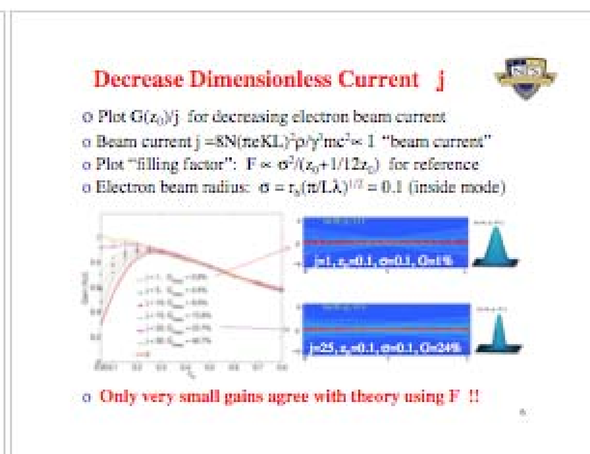
Optimum “Filling Factor” Question
o FEL coupling, Gain $\propto \rho F$ = “electron beam density” x F
o So Gain G $\propto 1/A_o$ independent of beam area A_e
o where $A_o(z)$ along undulator length of length L is
o $A_o(z) = \pi w(z)^2 = \pi w_0^2(1+(z\text{-}L/2)^2/Z_0^2)$ along z
o where Rayleigh length is $Z_0 = \pi w_0^2/\lambda$,
w_0 = optical mode waist, λ = optical wavelength
o Average $A_o(z)$ over undulator length ($z = 0 \to L$)
$< A_o(z) > = \pi \int dz w(z)^2/L = \lambda(Z_0+L^2/12Z_0)$
o Minimizing $< A_o(z) >$ gives maximum Gain G
o when $Z_0 = L/12^{1/2} \approx 0.3L$
$z \to$
o Is this truly a maximum for FEL Gain ??
3



Vary Rayleigh Length
o Normalized Rayleigh length $z_0 = Z_0/L$
o Mode area at mirrors is $A_{S/2} \propto 1/z_0$
as desired to reduce mirror intensity
o Mode area at waist is $A_0 \propto z_0$
o Simple theory: G $\propto$ F (filling factor)
o G_{max} at $z_0 = (12)^{-1/2}$; $Z_0 = L/(12)^{1/2}$
o Simulation allows many optical modes:
o Gain G increases for small z_0 values !!
o Small $Z_0 \Rightarrow$ still good gain !!
o What is the valid range of parameters for the “filling factor” concept ???
F
z_0
4



Decrease Beam Current, Check Lower Gains
o Reduce peak current:
I = 400A to I = 100A
o Gain still large at small Z_0 !!
o Reduce peak current further:
I_{peak} = 100A, and I_{peak} = 55A
o Gain remains up $\approx$ 25% at small Z_0 !!
o What gain is low enough for the filling factor concept ??
z_0
5



Decrease Dimensionless Current j
o Plot $G(z_0)/j$ for decreasing electron beam current
o Beam current $j = 8N(\pi eKL)^2\rho/\gamma^3mc^2 \propto I$ “beam current”
o Plot “filling factor”: $F \propto \sigma^2/(z_0+1/12z_0)$ for reference
o Electron beam radius: $\sigma = r_b(\pi/L\lambda)^{1/2} = 0.1$ (inside mode)
j=1, z_0=0.1, σ=0.1, G=1%
j=25, z_0=0.1, σ=0.1, G=24%
o Only very small gains agree with theory using F !!
6

Presentation at 27th International FEL Conference, Stanford, California, September 2005

Simulations of the Jefferson Lab FEL Using the New Electromagnetic Wiggler

W.B. Colson, J. Blau, O.E. Bowlin, B. Williams, R. Vigil and T. Voughs

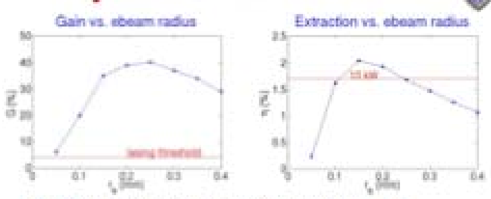
Physics Department
Naval Postgraduate School
Monterey, California 93943 USA

International FEL Conference, Stanford, CA, Aug 2005

Outline

- Jefferson Lab recently installed a new EM wiggler in their FEL
  - Shorter undulator period (8 cm) to obtain 1 μm light
  - Can be used with a short-Rayleigh length optical cavity
- Use numerical simulations to study FEL design parameters
  - Electron beam: bunch charge, pulse length, and waist radius
  - Optical cavity: Rayleigh length, output coupling
- Also study system vibration tolerances
  - Mirror shift and tilt
  - Electron beam shift and tilt

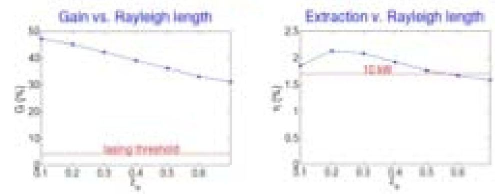
Vary electron beam radius



- Bunch charge and transverse emittance held constant
- Smaller beam radius ⇒ higher peak current ⇒ increased angular spread

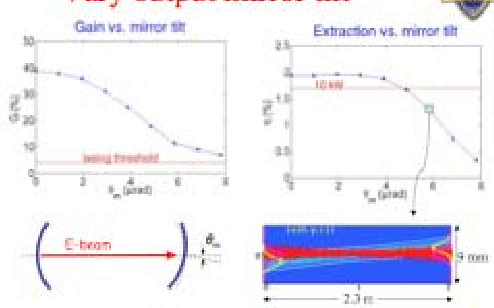
- Optimum gain, extraction at $r_b \approx 0.2$ mm (radius at beam waist)

Vary Rayleigh length



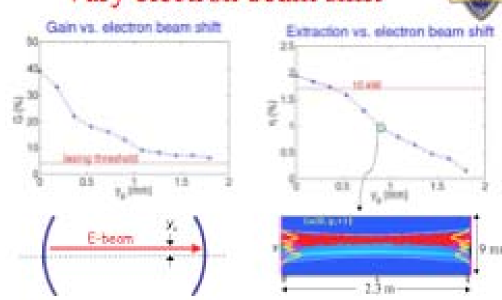
- Rayleigh length $z_0 = Z_0/L$ normalized to undulator length
- Gain increases as z_0 decreases
- Optimum extraction at $z_0 = 0.2$
- Smaller z_0 ⇒ reduced mirror intensity

Vary output mirror tilt

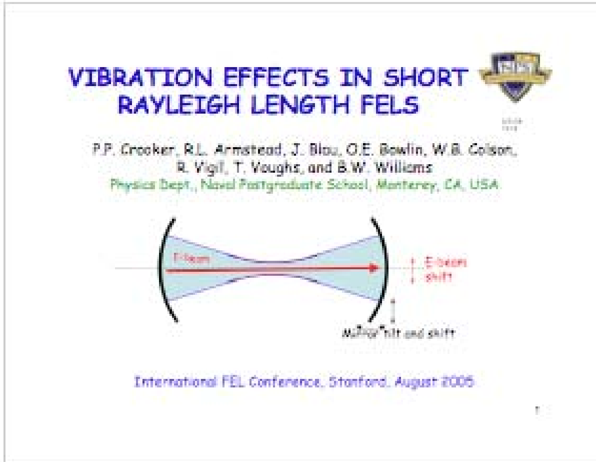


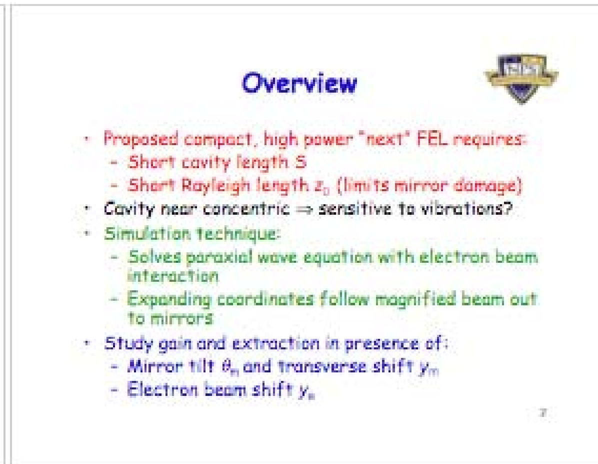
- Output mirror tilt ⇒ optical mode tilt
- Output power > 10 kW for mirror tilt < 5 μrad

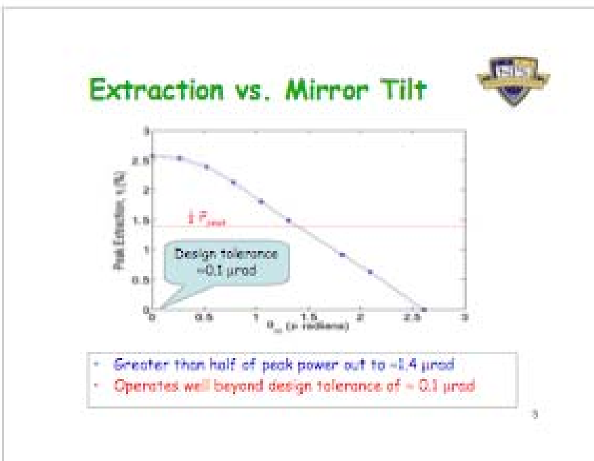
Vary electron beam shift

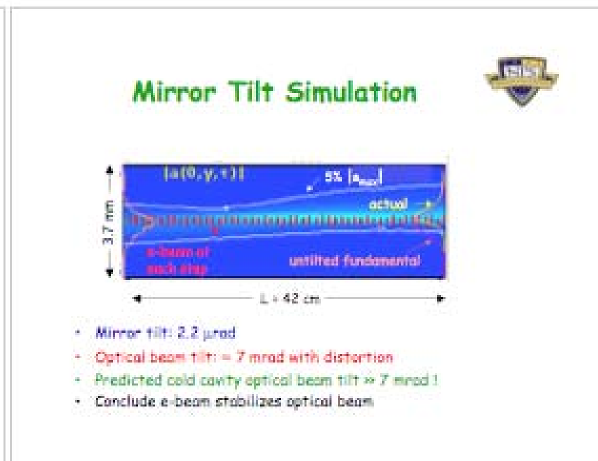


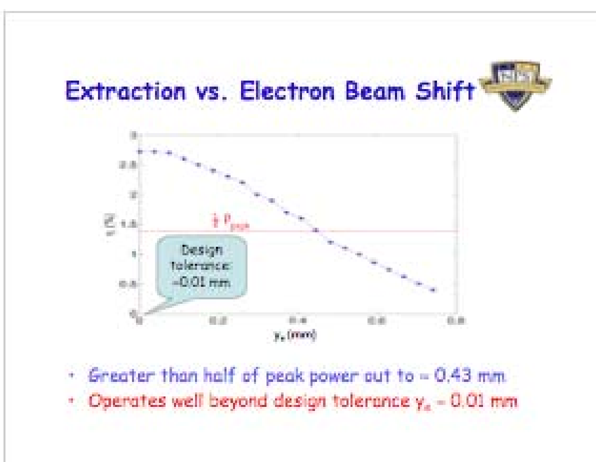
- Electron beam shifted off cavity axis ⇒ higher-order modes
- Output power > 10 kW for electron beam shift < 0.5 mm

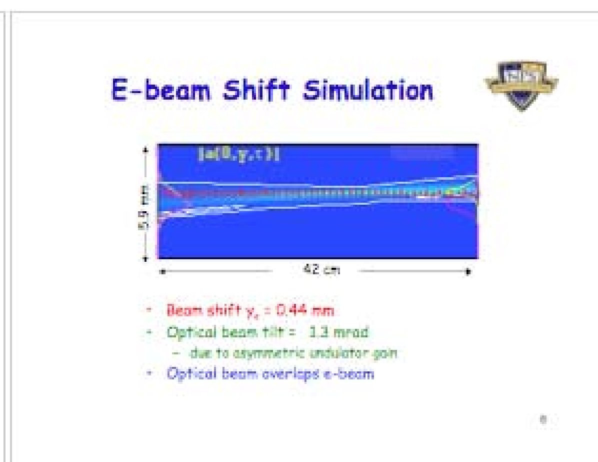

VIBRATION EFFECTS IN SHORT RAYLEIGH LENGTH FELS
P.P. Crooker, R.L. Armstead, J. Blau, O.E. Bowlin, W.B. Colson, R. Vigil, T. Voughs, and B.W. Williams
Physics Dept., Naval Postgraduate School, Monterey, CA, USA
E-beam
E-beam shift
Mirror tilt and shift
International FEL Conference, Stanford, August 2005
1


Overview
Proposed compact, high power "next" FEL requires:
- Short cavity length S
- Short Rayleigh length z_0 (limits mirror damage)
Cavity near concentric ⇒ sensitive to vibrations?
Simulation technique:
- Solves paraxial wave equation with electron beam interaction
- Expanding coordinates follow magnified beam out to mirrors
Study gain and extraction in presence of:
- Mirror tilt θ_m and transverse shift y_m
- Electron beam shift y_e
2

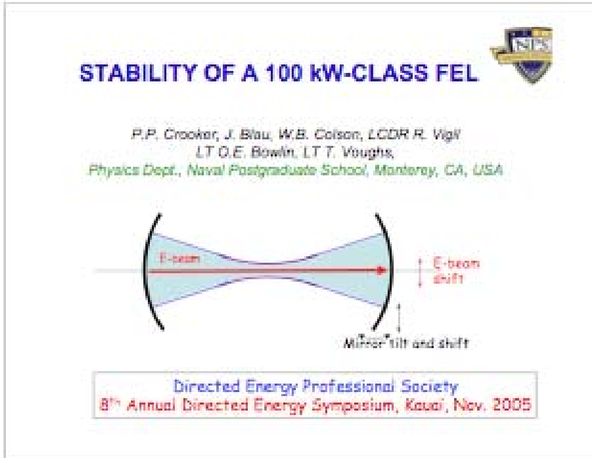

Extraction vs. Mirror Tilt
Peak Extraction, η (%)
$\frac{1}{2} P_{peak}$
Design tolerance ~0.1 μrad
θ_m (μ radians)
Greater than half of peak power out to ~1.4 μrad
Operates well beyond design tolerance of ~ 0.1 μrad
3

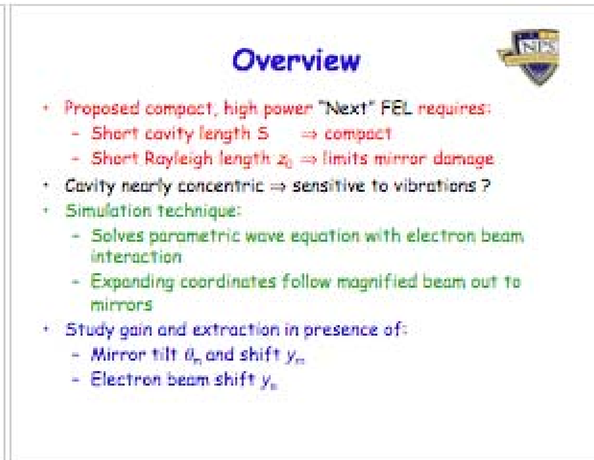

Mirror Tilt Simulation
|a(0,y,τ)|
5% $|a_{max}|$
actual
e-beam at each step
untilted fundamental
3.7 mm
L = 42 cm
Mirror tilt: 2.2 μrad
Optical beam tilt: ≈ 7 mrad with distortion
Predicted cold cavity optical beam tilt » 7 mrad !
Conclude e-beam stabilizes optical beam

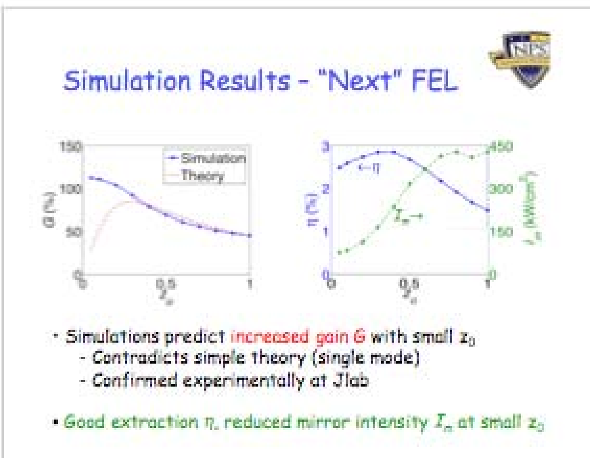

Extraction vs. Electron Beam Shift
η (%)
$\frac{1}{2} P_{peak}$
Design tolerance: ~0.01 mm
y_e (mm)
Greater than half of peak power out to ≈ 0.43 mm
Operates well beyond design tolerance y_e ~ 0.01 mm

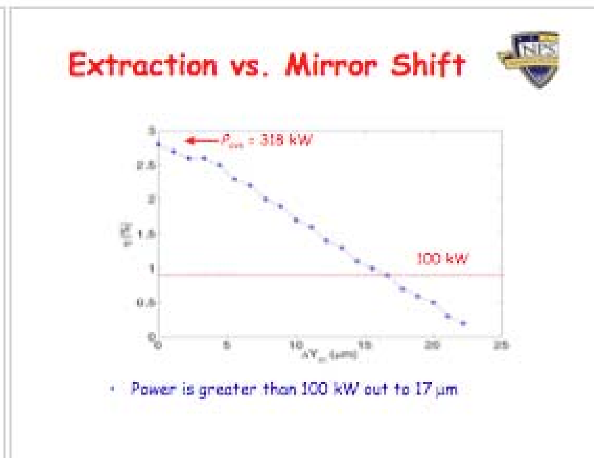

E-beam Shift Simulation
|a(0,y,τ)|
5.9 mm
42 cm
Beam shift y_e = 0.44 mm
Optical beam tilt = 1.3 mrad
- due to asymmetric undulator gain
Optical beam overlaps e-beam
6

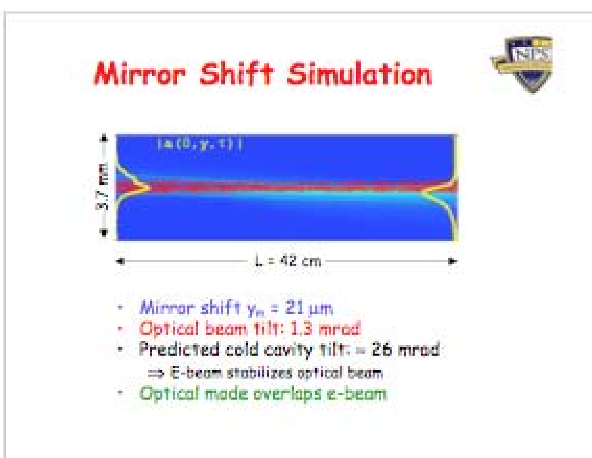
Presentation at 8th Directed Energy Symposium, Kauai, HI, November 2005



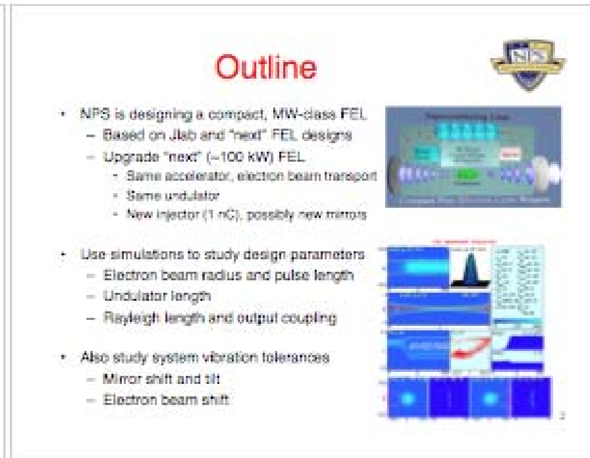


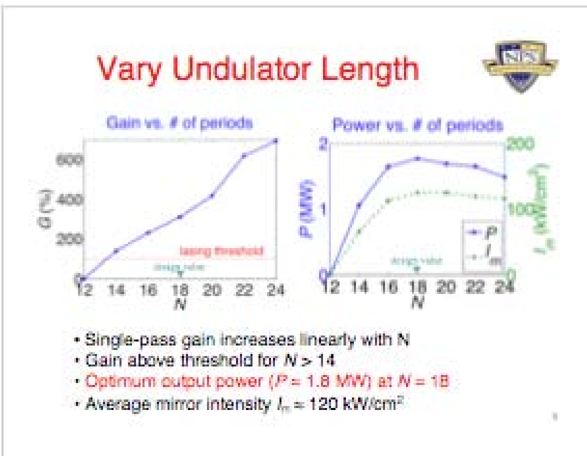


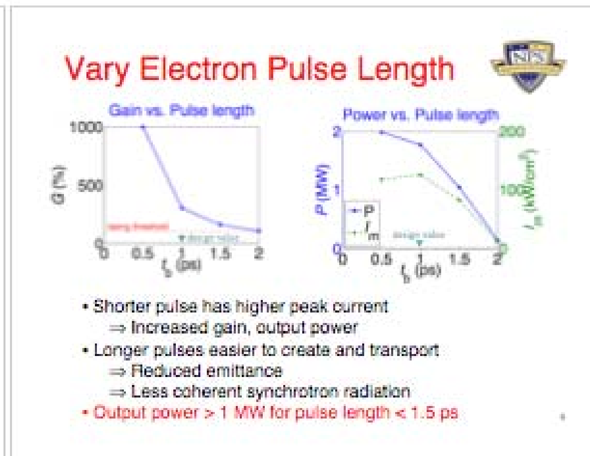


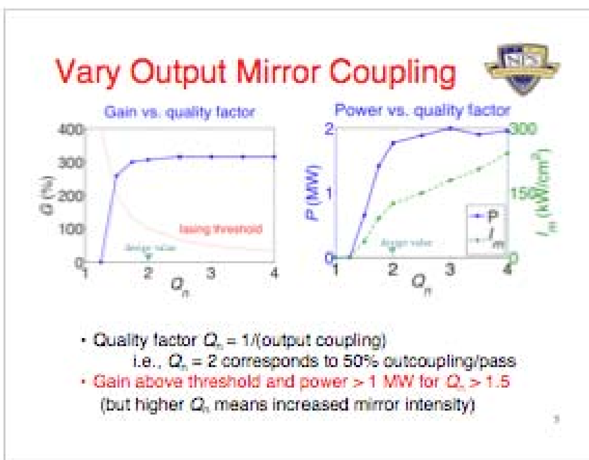


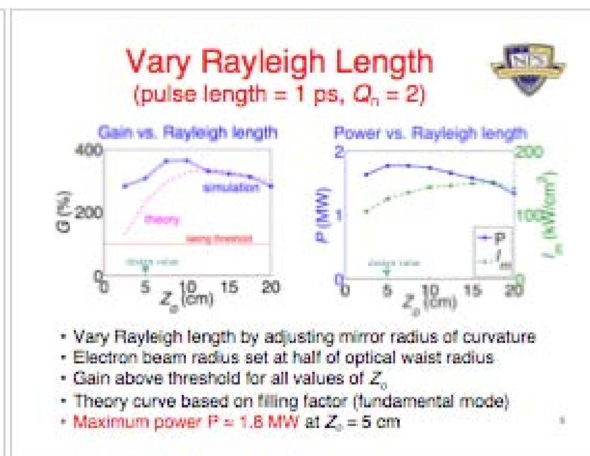

Design of a MW-class FEL
LCDR R. Vigil, LT O.E. Bowlin, LT T. Voughs
W.B. Colson, J. Blau and P.P. Crooker
Directed Energy and Electric Weapons Center
Physics Department, Naval Postgraduate School
Monterey, California 93943 USA
8th Annual Directed Energy Professional Society Symposium, Kauai, Nov 2005
1


Outline
• NPS is designing a compact, MW-class FEL
– Based on Jlab and "next" FEL designs
– Upgrade "next" (~100 kW) FEL
• Same accelerator, electron beam transport
• Same undulator
• New injector (1 nC), possibly new mirrors
• Use simulations to study design parameters
– Electron beam radius and pulse length
– Undulator length
– Rayleigh length and output coupling
• Also study system vibration tolerances
– Mirror shift and tilt
– Electron beam shift
2


Vary Undulator Length
Gain vs. # of periods
Power vs. # of periods
G (%)
P (MW)
N
lasing threshold
design value
• Single-pass gain increases linearly with N
• Gain above threshold for N > 14
• Optimum output power (P ≈ 1.8 MW) at N = 18
• Average mirror intensity Im ≈ 120 kW/cm²
3


Vary Electron Pulse Length
Gain vs. Pulse length
Power vs. Pulse length
G (%)
P (MW)
• Shorter pulse has higher peak current
⇒ Increased gain, output power
• Longer pulses easier to create and transport
⇒ Reduced emittance
⇒ Less coherent synchrotron radiation
• Output power > 1 MW for pulse length < 1.5 ps
4


Vary Output Mirror Coupling
Gain vs. quality factor
Power vs. quality factor
G (%)
P (MW)
lasing threshold
design value
• Quality factor Qn = 1/(output coupling)
i.e., Qn = 2 corresponds to 50% outcoupling/pass
• Gain above threshold and power > 1 MW for Qn > 1.5
(but higher Qn means increased mirror intensity)
5


Vary Rayleigh Length
(pulse length = 1 ps, Qn = 2)
Gain vs. Rayleigh length
Power vs. Rayleigh length
G (%)
P (MW)
simulation
theory
lasing threshold
design value
• Vary Rayleigh length by adjusting mirror radius of curvature
• Electron beam radius set at half of optical waist radius
• Gain above threshold for all values of Z0
• Theory curve based on filling factor (fundamental mode)
• Maximum power P ≈ 1.8 MW at Z0 = 5 cm
6

SIMULATIONS OF THE JEFFERSON LAB FEL USING THE NEW ELECTROMAGNETIC WIGGLER *

J. Blau†, W.B. Colson, B.W. Williams, O.E. Bowlin, R. Vigil and T. Voughs,
Physics Department, Naval Postgraduate School, Monterey, CA 93943, USA

Abstract

After successfully lasing at 10 kW of average power at a wavelength of 6 μm, a new electromagnetic wiggler has been installed at Jefferson Lab, which will be used to achieve high power at shorter wavelengths. Wavefront propagation simulations are used to predict system performance for weak-field gain and steady-state extraction, as the bunch charge, pulse length, electron beam radius, Rayleigh length, and mirror output coupling are varied.

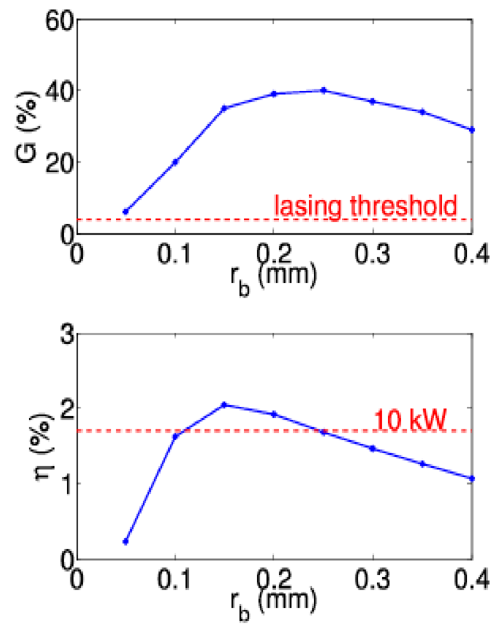


Figure 3: Weak-field gain G and steady-state extraction η versus electron beam waist radius, r_b. The optimum radius is $r_b \approx 0.2$ mm.

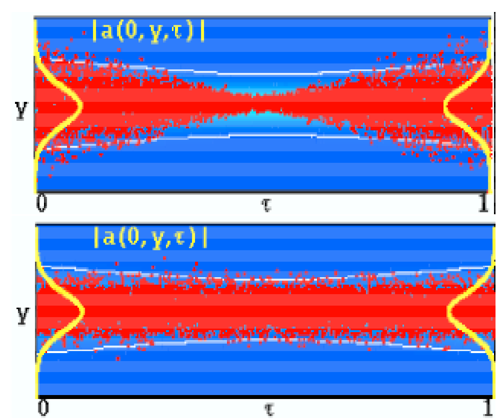


Figure 4: Simulation output showing a cross-section of the optical field amplitude $|a(y,\tau)|$ over a single pass through the undulator, with red dots representing sample electrons, for a narrow electron beam with waist radius $r_b = 0.1$ mm (top), and a broad electron beam with $r_b = 0.4$ mm (bottom). The yellow curves depict the optical mode profile $|a(y)|$ at the beginning ($\tau = 0$) and end ($\tau = 1$) of the undulator. The white line represents 5% of the peak optical field amplitude $|a|$.

Proceedings of the 27th International Free Electron Laser Conference

VIBRATION EFFECTS IN SHORT RAYLEIGH LENGTH FELS*

P.P. Crooker †, R.L. Armstead, J. Blau, O.E. Bowlin, W.B. Colson,
R. Vigil, T. Voughs, and B.W. Williams
Naval Postgraduate School, Monterey, CA, USA

Abstract

The short-Rayleigh length FEL configuration leaves the optical resonator near the cold-cavity stability limit. Studies show that the electron beam interaction stabilizes the optical modes and establishes limits to the vibrations of mirrors and the electron beam. Several types of vibrations are considered.

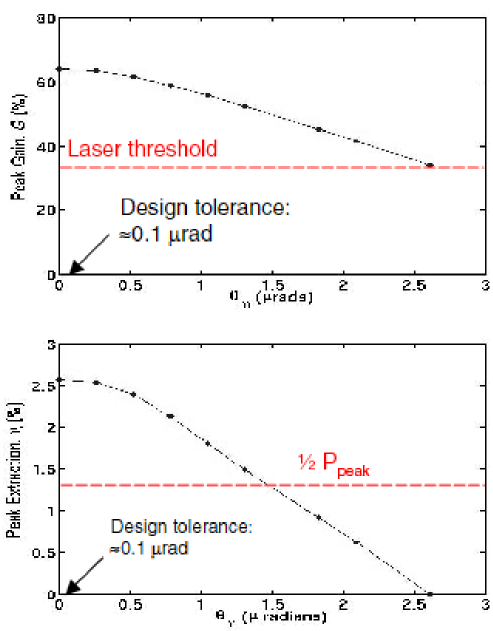


Figure 2: Dependence of weak-field gain and extraction on mirror tilt angle. Lasing continues out to 2.5 μrad; no appreciable change occurs over the current design tolerance of ≈ 0.1 μrad.

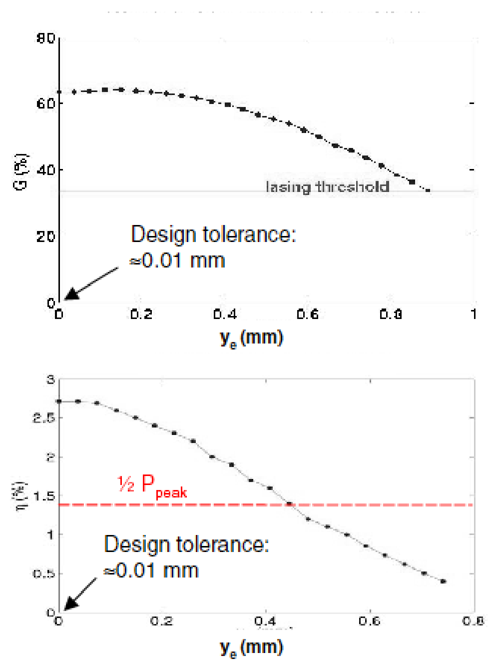


Figure 5: Dependence of weak field gain and extraction on electron beam shift. The half-power tolerance of 0.4 mm is well beyond design tolerance ≈ 10 μm.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 040703 (2005)

Stability of a short Rayleigh length laser resonator

P. P. Crooker,* J. Blau, and W. B. Colson

Physics Department, Naval Postgraduate School, 833 Dyer Road, Monterey, California 93943, USA

(Received 4 January 2005; published 22 April 2005)

Motivated by the prospect of constructing a short Rayleigh length free-electron laser in a high-vibration environment, we demonstrate the use of a collection of rays to study the effect of mirror vibration and distortion on the behavior of the fundamental optical mode of a cold-cavity resonator. We find that the ray collection accurately describes both on-axis and off-axis optical beams. We show that a tilt or transverse shift of a mirror causes the optical mode to rock about the original resonator axis, while a longitudinal mirror shift or a change in the mirror's radius of curvature causes the beam diameter at a mirror to successively dilate and contract on the mirror. Results are in excellent agreement with analytic calculations and wave front propagation simulations as long as the mirrors remain large with respect to the beam diameter.

DOI: 10.1103/PhysRevSTAB.8.040703 PACS numbers: 61.30.Cz, 64.70.Md

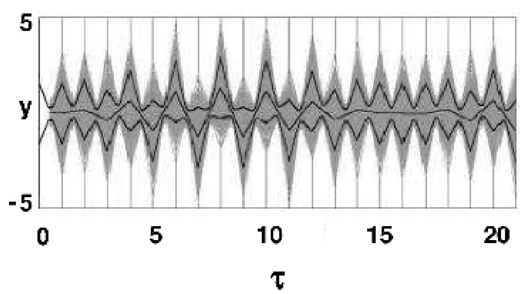


FIG. 2. Evolution of an optical beam in a resonator with $z_0 = 0.1$, $\theta_m = 0.05$, and $h = 0$. The y axis is the normalized transverse distance, and τ is the normalized time. Each vertical line corresponds to a mirror, with successive reflections unfolded to see the overall behavior. The shaded area shows the trajectories of 1000 random rays; the center line is the center of the optical beam; and the top and bottom lines, calculated from beam theory, correspond to the radius w for the Gaussian mode. The effect of mirror tilt is to make the beam rock back and forth on the resonator mirrors.

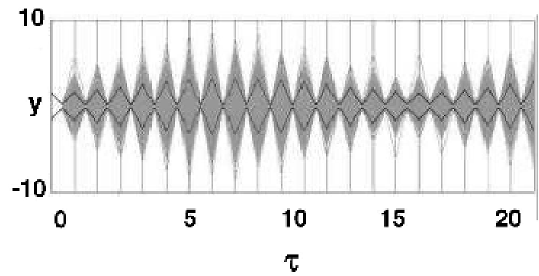


FIG. 4. Evolution of an optical beam in a resonator with $z_0 = 0.1$ and right mirror shift $\Delta s = 0.031$. The axes are the same as Fig. 2. The gray areas are the trajectories of 1000 random rays; the dotted lines, calculated from beam theory, correspond to the radius w of the Gaussian mode. The beam remains on axis, but expands and contracts with successive reflections.

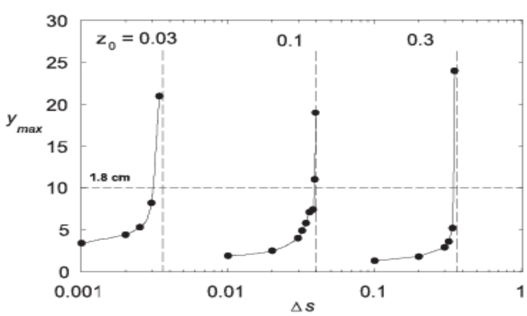


FIG. 5. Maximum beam radius $y_{\max}$ for fractional mirror shift Δs of the right-hand mirror at several values of z_0. As Δs increases, $y_{\max}$ diverges where the cavity becomes spherical at $\Delta s_{\max} = 4z_0^2$ (vertical dashed lines). The data points are taken from ray and beam simulations; the solid lines are guides to the eye. For an FEL with $S = 10$ m and $\lambda = 1\ \mu$m, $y_{\max} = 10$ corresponds to 1.8 cm.

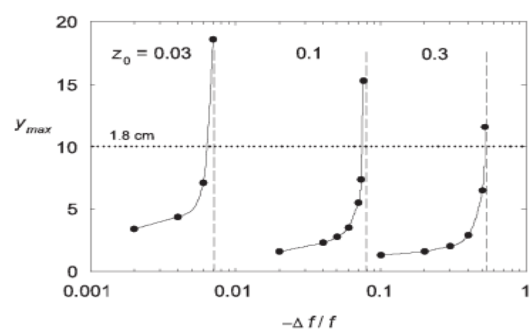


FIG. 7. Maximum beam radius $y_{\max}$ for fractional focal length change $\Delta f/f$ of the right-hand mirror at several values of z_0. The minus sign in front of $\Delta f/f$ indicates the focal length is decreasing. As the focal length decreases, $y_{\max}$ diverges where the cavity becomes spherical at $\Delta f/f = -8z_0^2/(1 + 4z_0^2)$ (vertical dashed lines). The points are taken from ray simulations and beam calculations; the solid lines are guides to the eye.

Higher-Order Modes in Free Electron Lasers

by

B. W. Williams

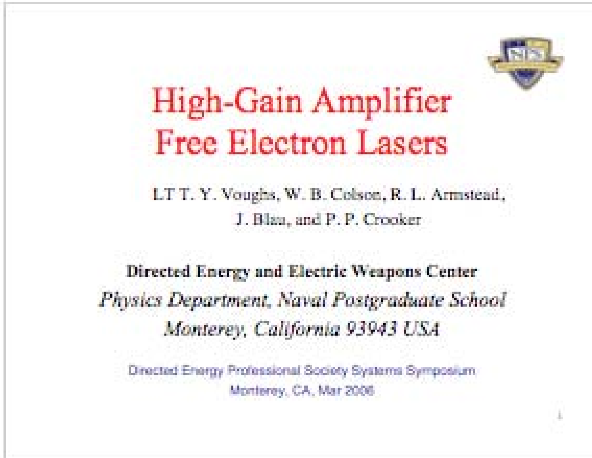
September 2005

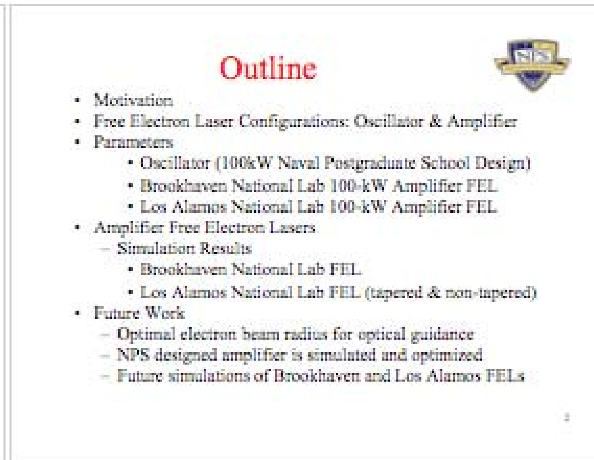
Thesis Advisor: W. B. Colson
Second Reader: R. Armstead

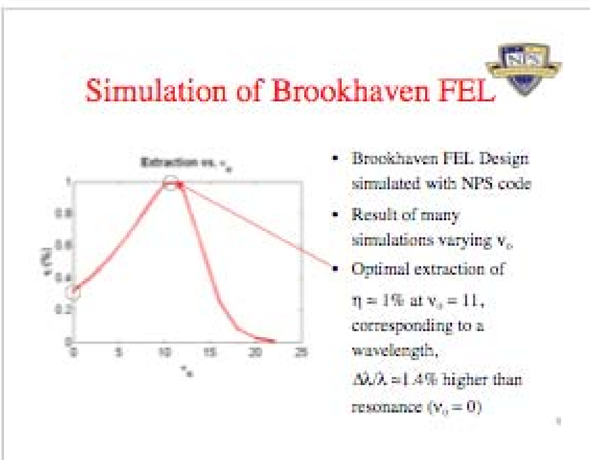
Free electron laser theory is developed from the Maxwell and Lorentz force equations; the properties and characteristics of the laser are reviewed. The wave equation is solved for the fundamental Gaussian mode, and higher-order modes in Cartesian and cylindrical coordinate spaces, yielding expressions for the complete and orthogonal basis sets of Hermite- and Laguerre-Gaussian beams. Motivated by the evident inclusion of higher-order modes in free electron laser simulations, a tool is developed for the higher-order (in particular Laguerre-Gaussian) modal analysis of simulated free electron laser beams.

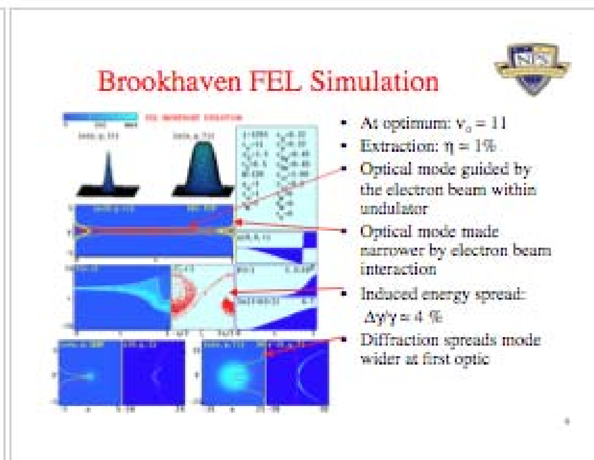
Figure 4.6: Each LG mode carries a different phase factor, causing periodic interference when multiple modes are combined.

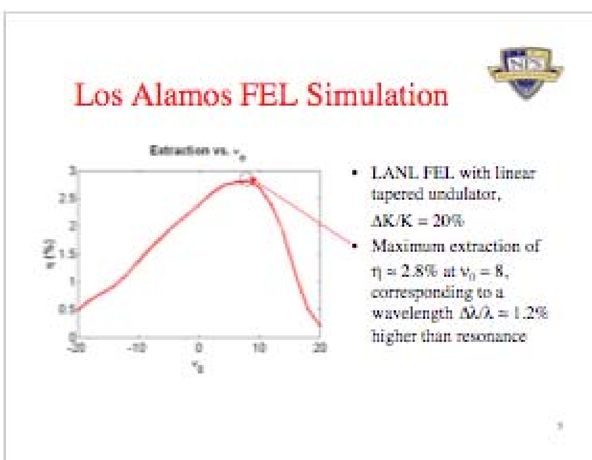
Presentation at Directed Energy Systems Symposium, Monterey, CA, March 2006

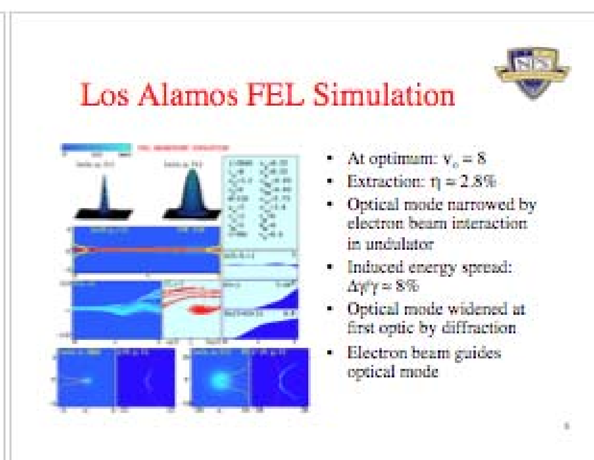


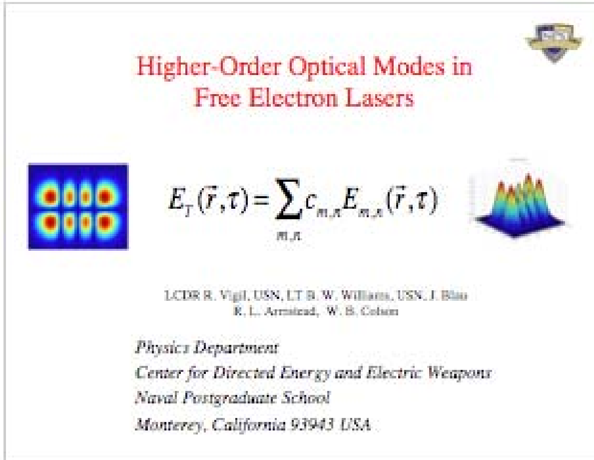


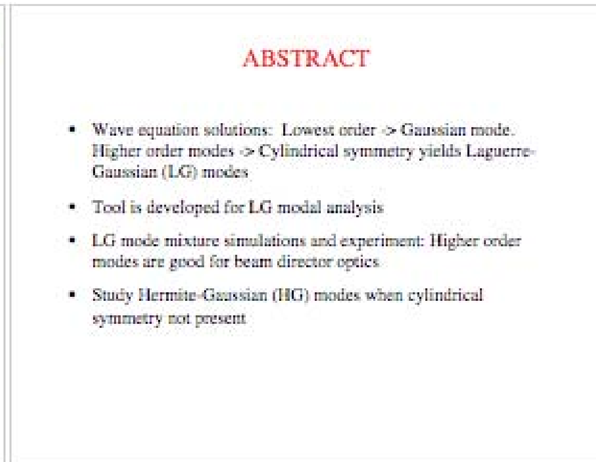


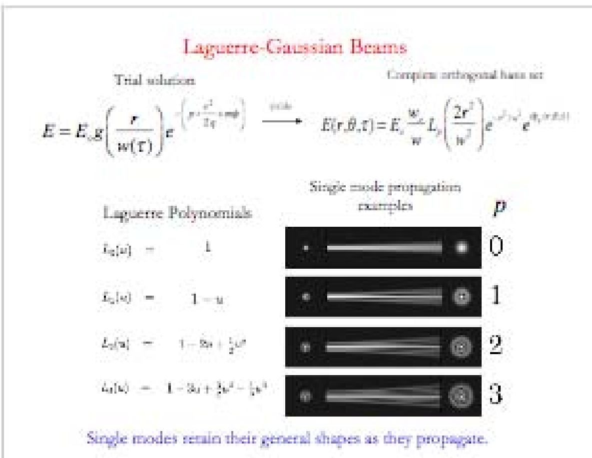


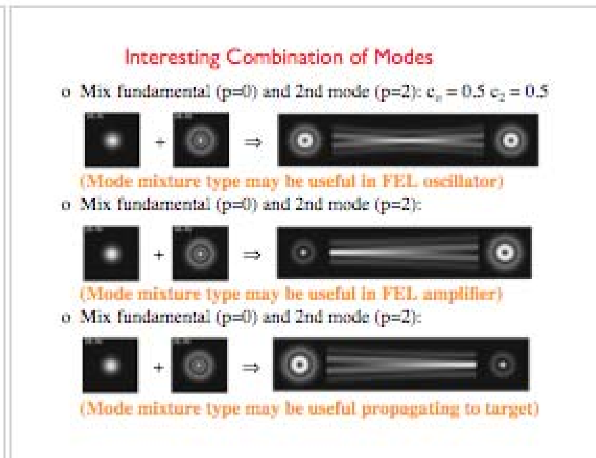


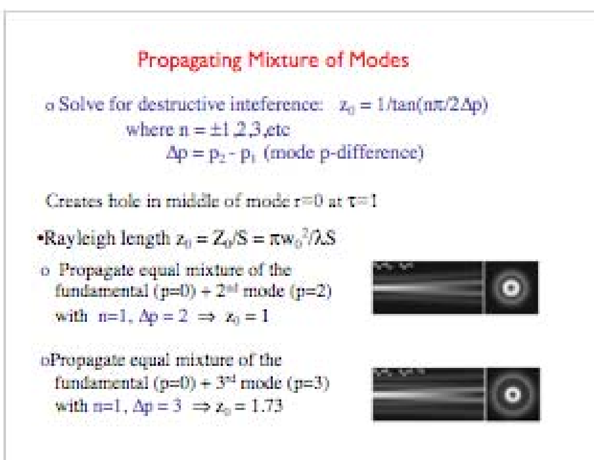


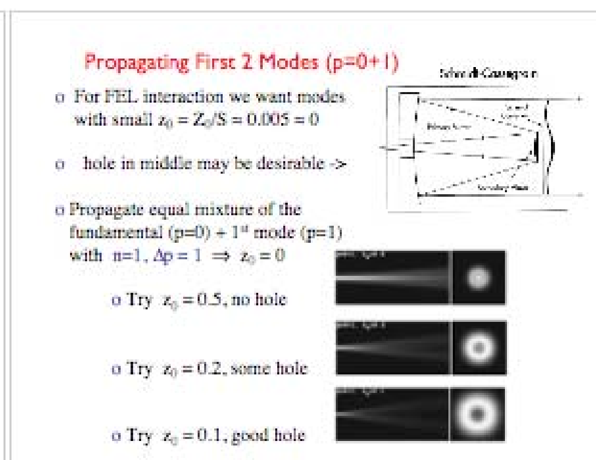

Higher-Order Optical Modes in Free Electron Lasers
$E_T(\vec{r},\tau)=\sum_{m,n} c_{m,n} E_{m,n}(\vec{r},\tau)$
LCDR R. Vigil, USN, LT B. W. Williams, USN, J. Blau
R. L. Armstead, W. B. Colson
Physics Department
Center for Directed Energy and Electric Weapons
Naval Postgraduate School
Monterey, California 93943 USA


ABSTRACT
• Wave equation solutions: Lowest order -> Gaussian mode. Higher order modes -> Cylindrical symmetry yields Laguerre-Gaussian (LG) modes
• Tool is developed for LG modal analysis
• LG mode mixture simulations and experiment: Higher order modes are good for beam director optics
• Study Hermite-Gaussian (HG) modes when cylindrical symmetry not present


Laguerre-Gaussian Beams
Trial solution
Complete orthogonal basis set
Single mode propagation examples
Laguerre Polynomials
p
0
1
2
3
Single modes retain their general shapes as they propagate.


Interesting Combination of Modes
o Mix fundamental (p=0) and 2nd mode (p=2): $c_o = 0.5$ $c_2 = 0.5$
(Mode mixture type may be useful in FEL oscillator)
o Mix fundamental (p=0) and 2nd mode (p=2):
(Mode mixture type may be useful in FEL amplifier)
o Mix fundamental (p=0) and 2nd mode (p=2):
(Mode mixture type may be useful propagating to target)


Propagating Mixture of Modes
o Solve for destructive inteference: $z_0 = 1/\tan(n\pi/2\Delta p)$
where $n = \pm1, 2, 3$, etc
$\Delta p = p_2 - p_1$ (mode p-difference)
Creates hole in middle of mode $r=0$ at $\tau=1$
•Rayleigh length $z_0 = Z_0/S = \pi w_0^2/\lambda S$
o Propagate equal mixture of the fundamental (p=0) + 2nd mode (p=2) with $n=1$, $\Delta p = 2 \Rightarrow z_0 = 1$
oPropagate equal mixture of the fundamental (p=0) + 3rd mode (p=3) with $n=1$, $\Delta p = 3 \Rightarrow z_0 = 1.73$


Propagating First 2 Modes (p=0+1)
o For FEL interaction we want modes with small $z_0 = Z_0/S = 0.005 = 0$
o hole in middle may be desirable ->
o Propagate equal mixture of the fundamental (p=0) + 1st mode (p=1) with $n=1$, $\Delta p = 1 \Rightarrow z_0 = 0$
o Try $z_0 = 0.5$, no hole
o Try $z_0 = 0.2$, some hole
o Try $z_0 = 0.1$, good hole

MODELING AND SIMULATION OF THE FREE ELECTRON LASER AND RAILGUN ON AN ELECTRIC NAVAL SURFACE PLATFORM

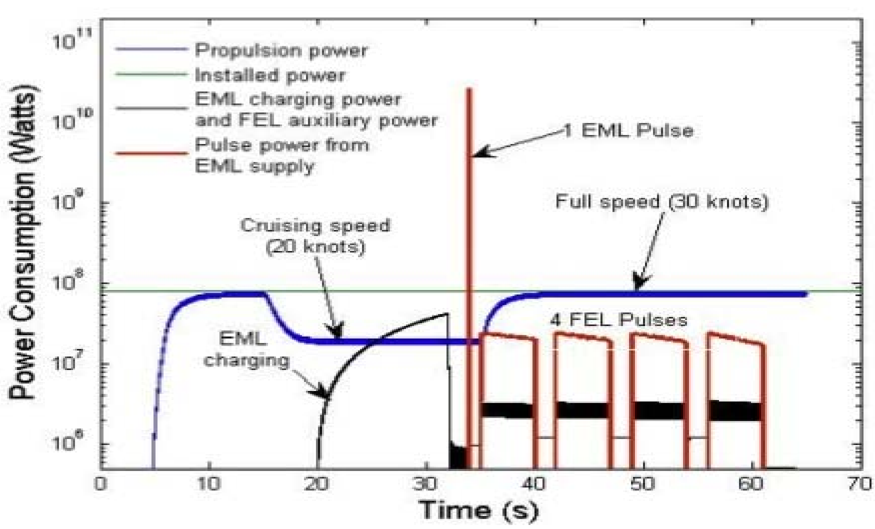
by

Oscar E. Bowlin

March 2006

Thesis Advisor: William B. Colson
Second Reader: Robert L. Armstead

The Free Electron Laser (FEL) and Rail Gun are electric weapons which will require a significant amount of stored energy for operation. These types of weapons are ideal for use onboard an all-electric ship. An investigation is made of the effects these weapons will have on a proposed electrical system architecture using simulation modeling. Specifically, this thesis identifies possible design weaknesses and shows where further research and modeling is needed in order to ensure the proper integration of these electric weapons onboard an all-electric ship. The integration of these electric weapon systems with the power systems on electric ships will have an impact on naval operations. Several scenarios concerning specific naval missions are investigated using simulation software to understand the impact and limitations on the electric system using these new electric weapons.



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **9**, 030703 (2006)

Short Rayleigh length free electron lasers

W. B. Colson, J. Blau, R. L. Armstead, P. P. Crooker, R. Vigil, T. Voughs, and B. W. Williams
Physics Department, Naval Postgraduate School, 833 Dyer Road, Monterey, California 93943, USA
(Received 30 November 2005; published 30 March 2006)

Conventional free electron laser (FEL) oscillators minimize the optical mode volume around the electron beam in the undulator by making the resonator Rayleigh length about one third to one half of the undulator length. This maximizes gain and beam-mode coupling. In compact configurations of high-power infrared FELs or moderate power UV FELs, the resulting optical intensity can damage the resonator mirrors. To increase the spot size and thereby reduce the optical intensity at the mirrors below the damage threshold, a shorter Rayleigh length can be used, but the FEL interaction is significantly altered. We model this interaction using a coordinate system that expands with the rapidly diffracting optical mode from the ends of the undulator to the mirrors. Simulations show that the interaction of the strongly focused optical mode with a narrow electron beam inside the undulator distorts the optical wave front so it is no longer in the fundamental Gaussian mode. The simulations are used to study how mode distortion affects the single-pass gain in weak fields, and the steady-state extraction in strong fields.

DOI: 10.1103/PhysRevSTAB.9.030703 PACS numbers: 41.60.Cr

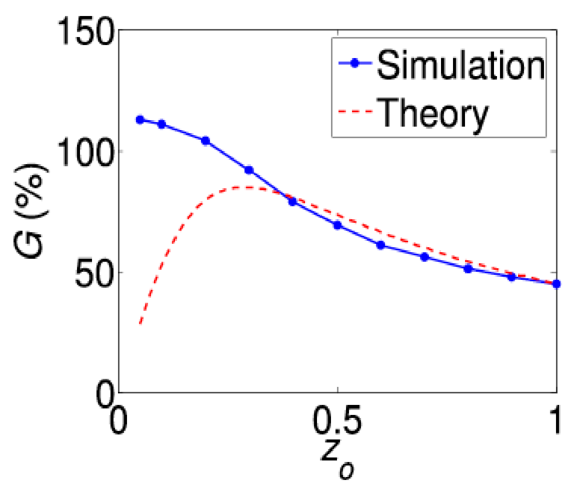


FIG. 5. (Color) Simulation results for FEL weak-field gain as a function of normalized Rayleigh length z_0 (solid blue line). The results are compared to a simple theory (dashed red line), which assumes the optical field is in the fundamental mode. The large disagreement between the simple theory and simulations for small z_0 is due to mode distortion.

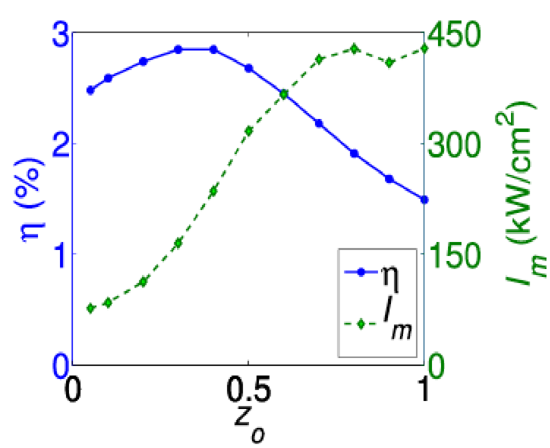


FIG. 6. (Color) Simulation results for extraction η versus normalized Rayleigh length z_0 (solid blue line). The optimum value is $z_0 \approx 0.3$, in agreement with the simple theory, but good extraction is maintained for smaller values of z_0. Also plotted is the intensity on the mirrors (dashed green line); the intensity decreases dramatically as the Rayleigh length is reduced.

HIGH-POWER AMPLIFIER FREE ELECTRON LASERS

by

Tyrone Y. Voughs

June 2006

Thesis Advisor: William B. Colson
Co-Advisor: Robert L. Armstead

The free electron laser (FEL) is among the latest technologies of interest to the U.S. military, in particular, the Navy. In naval applications, FEL laser would serve as a self-defense weapon system, protecting the ship from an array of threats including anti-surface cruise missiles and small boats. This system's potential range and deep magazine makes it ideal as point defense against incoming missiles. Its inexpensive cost of only a few dollars per engagement and multi-mission capability makes this future weapon system superior to the short-range missile-defense systems employed today. The most powerful FEL is currently located in Jefferson Lab, operating at 10 kW, two orders of magnitude short of the 1 MW power level required for weapons application. This thesis will describe the components and theory of operation of the FEL, as well as analyze two competing designs for the next step in the evolution of the future weapon system, the 100 kW FEL, proposed by Brookhaven and Los Alamos National Labs. Due to advances in NPS simulation techniques for the amplifier configuration, a more in depth analysis including the effects of electron beam tilt and shift is performed for the first time on these proposed designs.

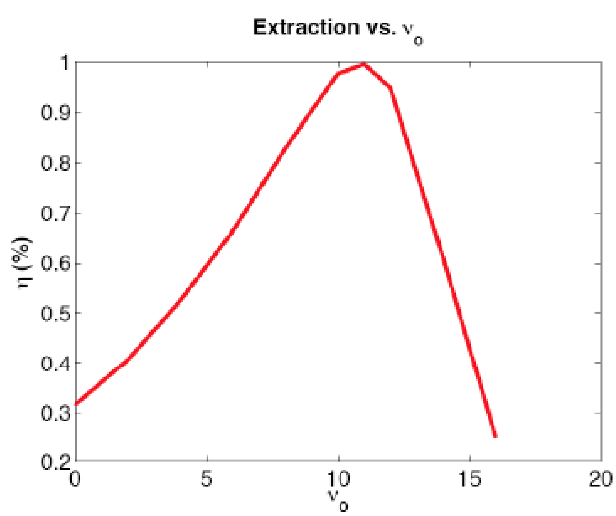


Figure 21. Brookhaven FEL Extraction Spectrum

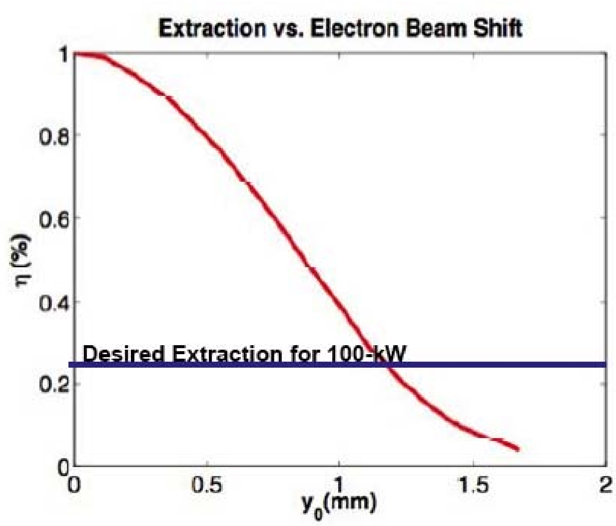


Figure 25. Extraction vs. Electron Beam Shift

HERMITE-GAUSSIAN MODES AND MIRROR DISTORTIONS IN THE FREE ELECTRON LASER

by

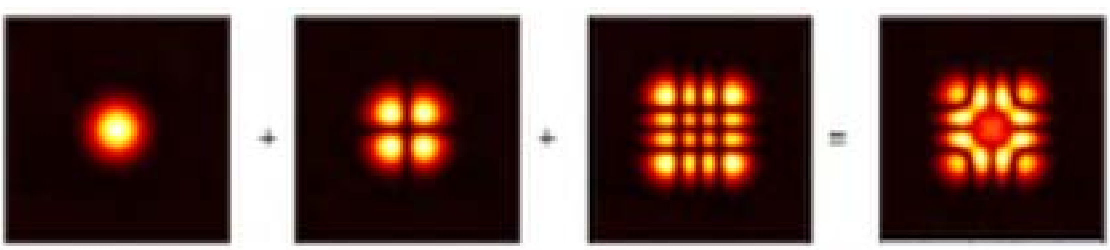
Ricardo Vigil

June 2006

Thesis Advisor: William Colson
Co-Advisor: Robert Armstead

The free electron laser (FEL) is proposed to meet the Navy's need for a speed-of-light high energy laser weapon capable of engaging a variety of targets including anti-ship cruise missiles, small boats, and theater ballistic missiles. A key attribute of FELs is good optical beam quality; in other words, they operate in only a few of the lowest-order transverse Gaussian modes. For weapons applications, a good mode quality is desired because it delivers the highest intensity on target ensuring a high level of lethality. A few higher-order modes can arise from the interaction of the electron beam with the optical beam, or from misalignments of the electron beam or resonator mirrors. High intensity on FEL optics can lead to mirror distortion due to heating and insufficient cooling of the mirror substrate. Mirror distortions, including astigmatism, can cause higher-order modes to appear affecting FEL performance. Therefore, it is important to quantify these higher-order modes because doing so uniquely identifies the optical field and may allow for corrective optics to single out the best modes for FEL lethality.

This thesis will review free electron laser theory, and for the first time develop analytical solutions to quantify Hermite-Gaussian higher-order modes, develop a diagnostic for modal analysis, and determine the tolerance limits on mirror distortions.



American Journal of Physics, Vol. 74, pp. 722-727 (August 2006)

Representation of a Gaussian beam by rays

P. P. Crooker,[a] W. B. Colson, and J. Blau
Physics Department, Naval Postgraduate School, Monterey, California 93943

(Received 3 October 2005; accepted 7 April 2006)

Although the ray concept is a useful tool for helping students visualize the propagation of light, rays do not produce diffraction, which is described by wave theory. Nevertheless, it is possible to retain the ray picture to describe a Gaussian beam if a suitable statistical distribution of rays is used. We transform the distribution using only ray propagation techniques (no wave theory) and show how a statistical distribution of rays gives an intuitive picture of a diffracting Gaussian beam as it freely propagates or is focused by lenses.
[DOI: 10.1119/1.2201857]

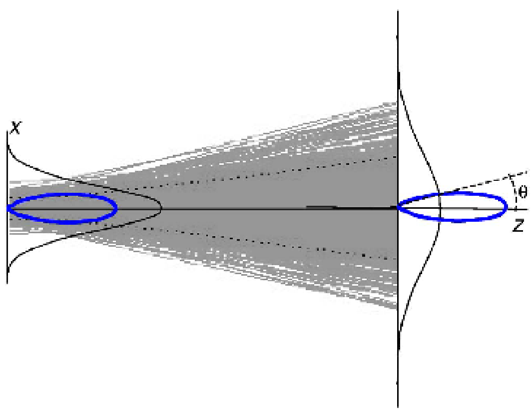


Fig. 2. Gaussian beam starting at the waist and spreading according to Eq. (4). The Gaussian widths are dashed lines. The Gaussian curves show $f(x)$; the loops are polar plots of $f(\theta)$. The shaded area is due to 1000 rays, distributed according to $f(x,\theta)$ and propagates as straight lines using ray matrices. As the beam propagates, the spatial width and density of the rays and of $f(x)$ follows Gaussian wave theory, while the angular distribution $f(\theta)$ remains unchanged.

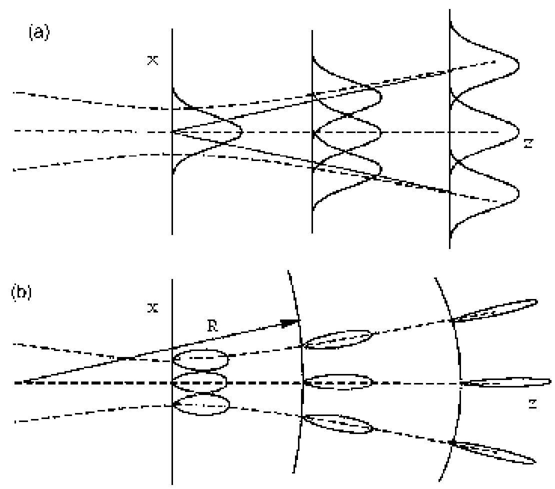
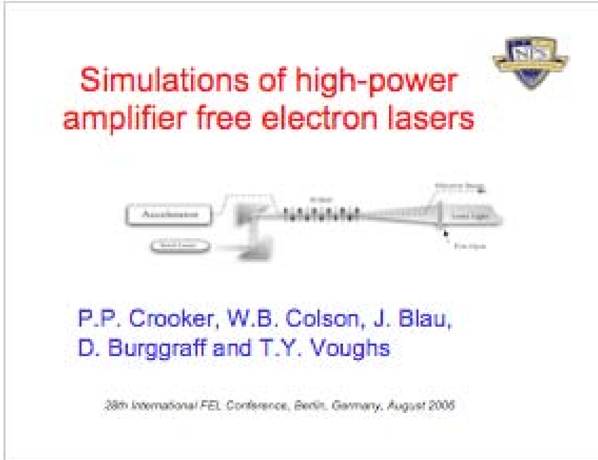
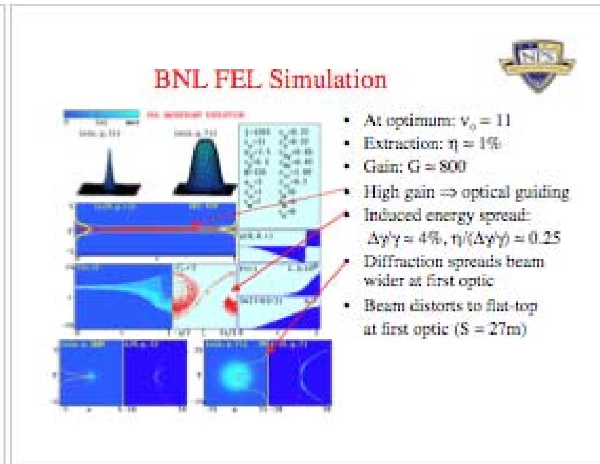
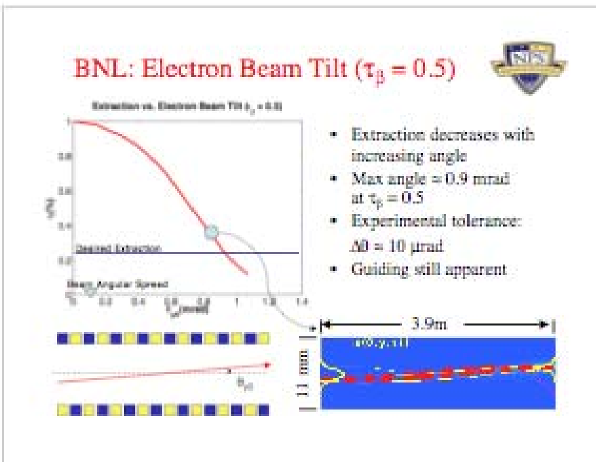


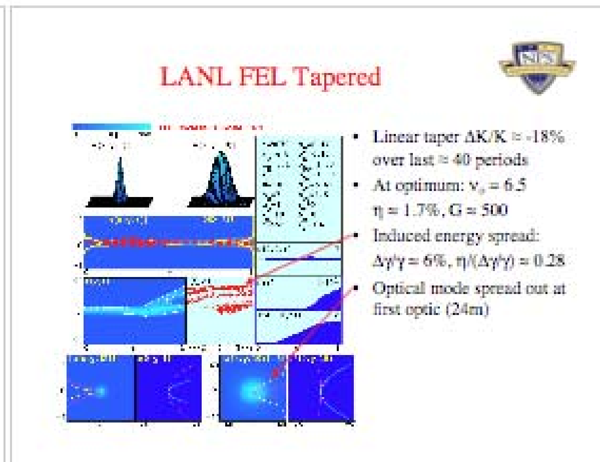
Fig. 3. Freely propagating Gaussian beam. (a) Gaussians representing $f(x|\theta)$; the widths are constant but are offset by $z\theta$ (solid straight lines). The dashed lines are the center and $1/e$ limits of the corresponding Gaussian beam. (b) Polar plots of $f(\theta|x)$. The distributions $f(\theta|x)$ are tilted by the angle x/R, which defines the direction of a statistical ray (dashed lines) and is always perpendicular to a wave front (solid arcs).

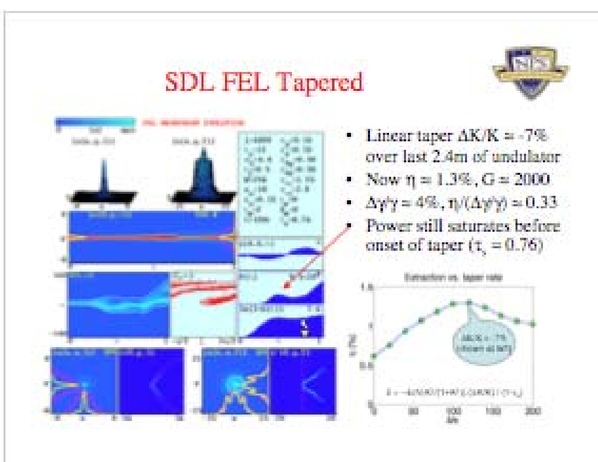
Presentation at 28th International FEL Conference, Berlin, Germany, September 2006

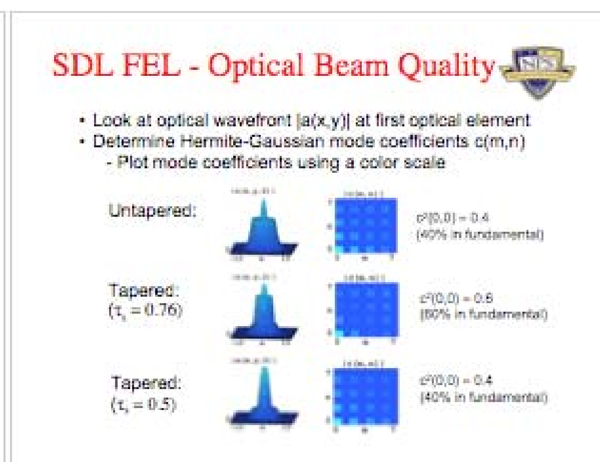


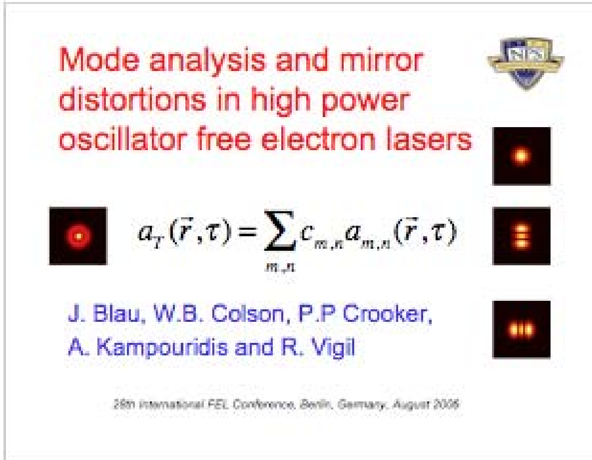


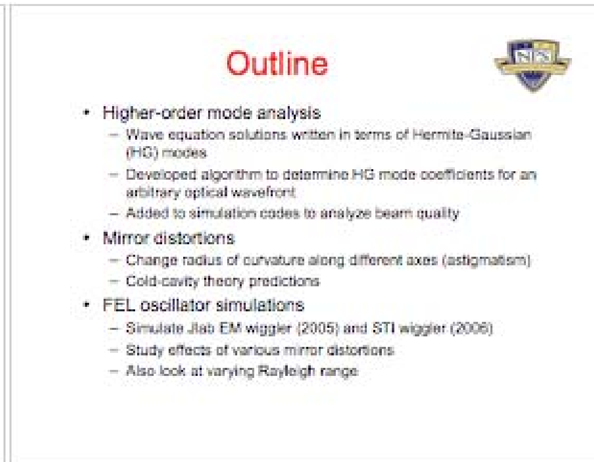


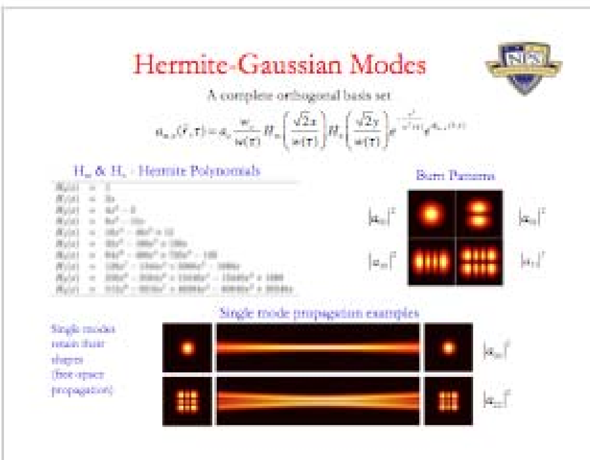


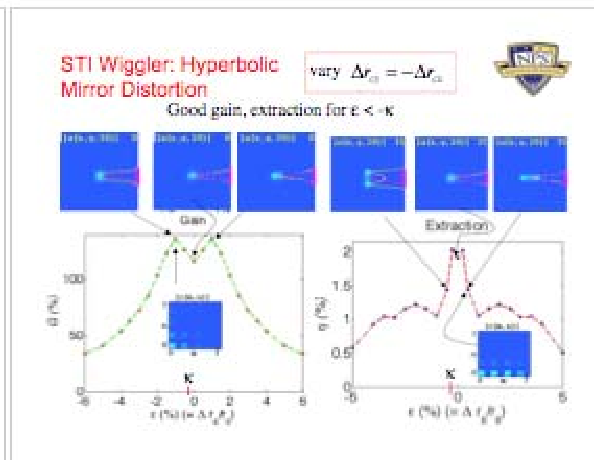


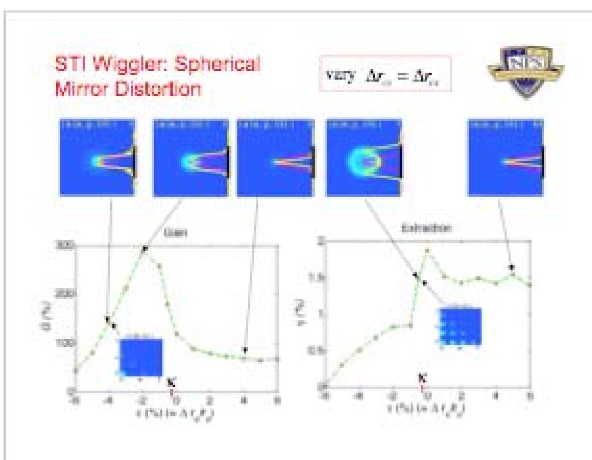


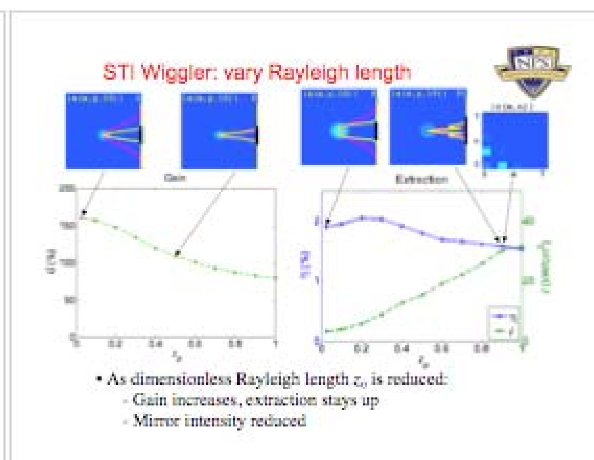

Mode analysis and mirror distortions in high power oscillator free electron lasers
$a_T(\vec{r},\tau)=\sum_{m,n} c_{m,n} a_{m,n}(\vec{r},\tau)$
J. Blau, W.B. Colson, P.P Crooker, A. Kampouridis and R. Vigil
28th International FEL Conference, Berlin, Germany, August 2006


Outline
Higher-order mode analysis
– Wave equation solutions written in terms of Hermite-Gaussian (HG) modes
– Developed algorithm to determine HG mode coefficients for an arbitrary optical wavefront
– Added to simulation codes to analyze beam quality
Mirror distortions
– Change radius of curvature along different axes (astigmatism)
– Cold-cavity theory predictions
FEL oscillator simulations
– Simulate Jlab EM wiggler (2005) and STI wiggler (2006)
– Study effects of various mirror distortions
– Also look at varying Rayleigh range


Hermite-Gaussian Modes
A complete orthogonal basis set
Burn Patterns
Single mode propagation examples


STI Wiggler: Hyperbolic Mirror Distortion
vary $\Delta r_{cy} = -\Delta r_{cx}$
Good gain, extraction for ε < -κ
Gain
Extraction
κ


STI Wiggler: Spherical Mirror Distortion
vary $\Delta r_{cy} = \Delta r_{cx}$
Gain
Extraction
κ


STI Wiggler: vary Rayleigh length
Gain
Extraction
As dimensionless Rayleigh length z_0 is reduced:
- Gain increases, extraction stays up
- Mirror intensity reduced

SIMULATIONS OF HIGH POWER-FEL AMPLIFIERS*

J. Blau, D. Burggraff, T.Y. Voughs and W.B. Colson
Physics Department, Naval Postgraduate School
333 Dyer Road, Monterey, CA 93943.

Abstract

FEL amplifier simulations have been updated and parallelized, and system vibration effects have been added. The simulations are used to study proposed high-power amplifier FELs at LANL and BNL. We look at the single-pass gain and output power, including the effects of wiggler tapering, electron beam pinching, and shifting and tilting of the electron beam.

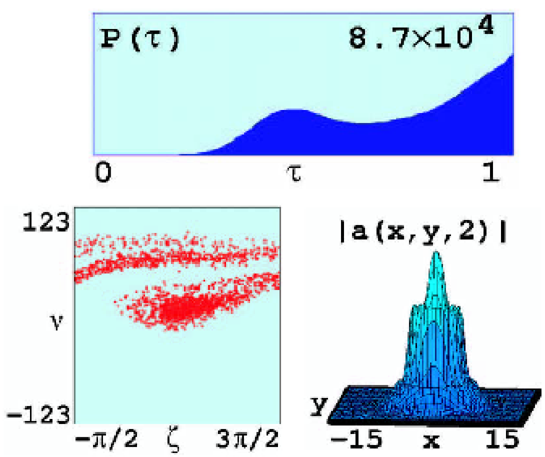


Figure 2: Simulation results for the SDL FEL with a -5% taper rate over the last 2.4 m of the undulator. On the top is the evolution of the optical power, $P(\tau)$. On the lower left is the final electron phase space as described in the text, with sample electrons shown in red. On the lower right is the final optical wavefront, $|a(x,y)|$, at the output mirror.

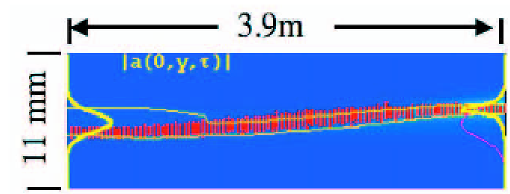
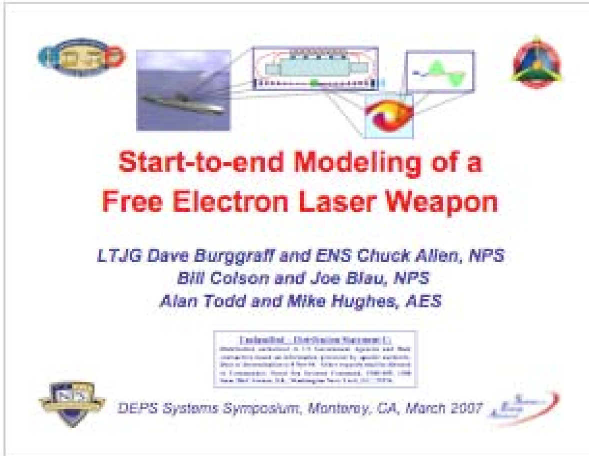
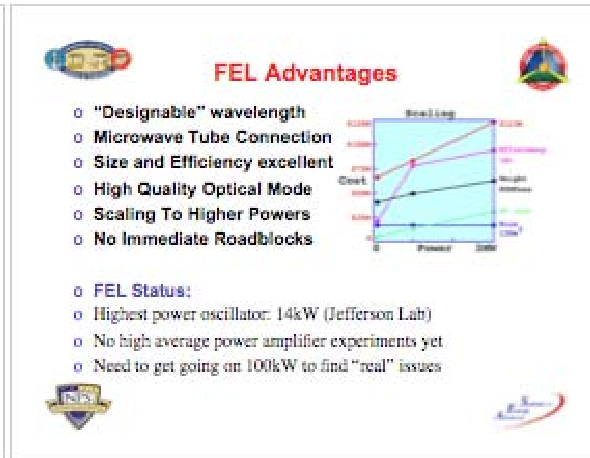
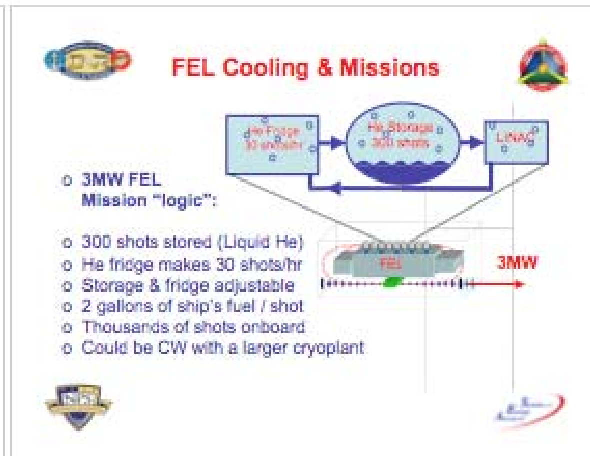


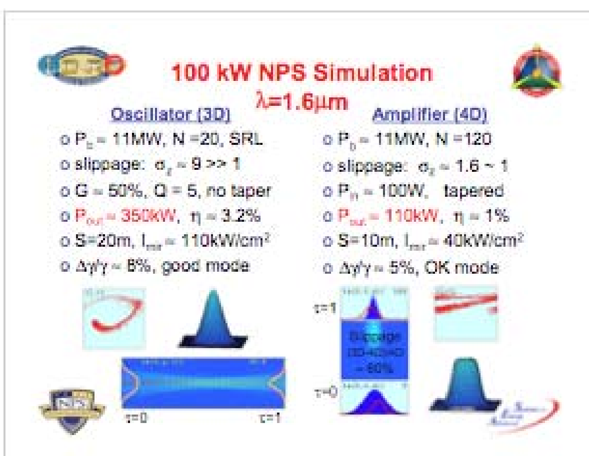
Figure 9: Optical field evolution for the proposed BNL FEL. Initial conditions are chosen so that the electron beam is tilted by $\theta_y = 0.9$ mrad at the center of the undulator. The tilt appears exaggerated due to the different horizontal and vertical scales. Notice that the optical mode (narrow yellow contour line) follows the tilted electron beam (red).

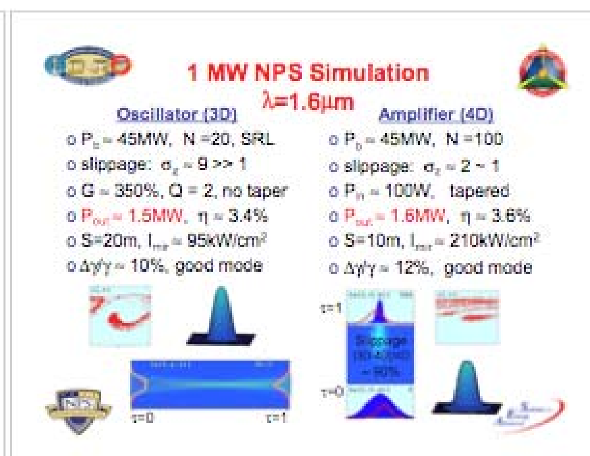

Start-to-end Modeling of a
Free Electron Laser Weapon
LTJG Dave Burggraff and ENS Chuck Allen, NPS
Bill Colson and Joe Blau, NPS
Alan Todd and Mike Hughes, AES
DEPS Systems Symposium, Monterey, CA, March 2007

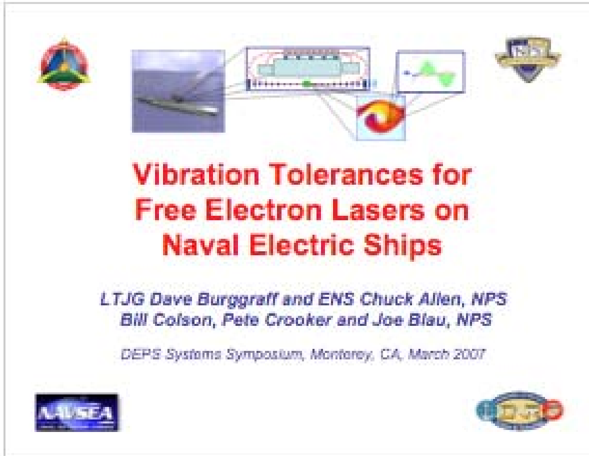

FEL Advantages
o "Designable" wavelength
o Microwave Tube Connection
o Size and Efficiency excellent
o High Quality Optical Mode
o Scaling To Higher Powers
o No Immediate Roadblocks
Scaling
Cost
Power
o FEL Status:
o Highest power oscillator: 14kW (Jefferson Lab)
o No high average power amplifier experiments yet
o Need to get going on 100kW to find "real" issues

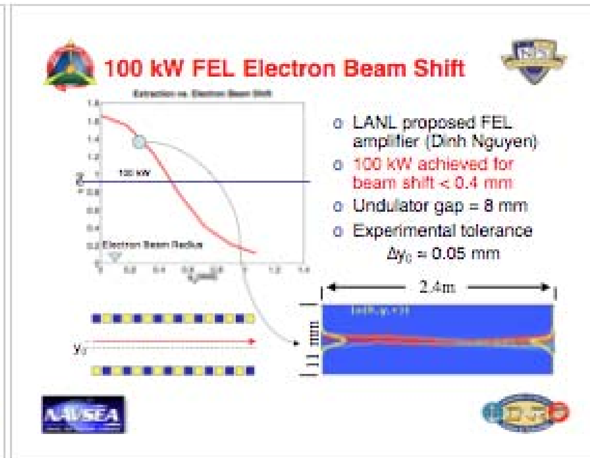

3 MW FEL Top Level Parameters
(current design - March 2007)
~2.5 m
< 20 m
TOTALS
12.9 MW
7.4 MW
9.7 MW
3.2 MW

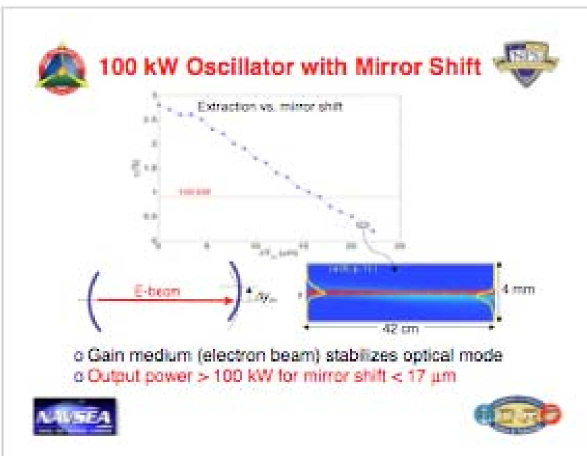

FEL Cooling & Missions
He Storage
300 shots
LINAC
o 3MW FEL
Mission "logic":
o 300 shots stored (Liquid He)
o He fridge makes 30 shots/hr
o Storage & fridge adjustable
o 2 gallons of ship's fuel / shot
o Thousands of shots onboard
o Could be CW with a larger cryoplant
FEL
3MW

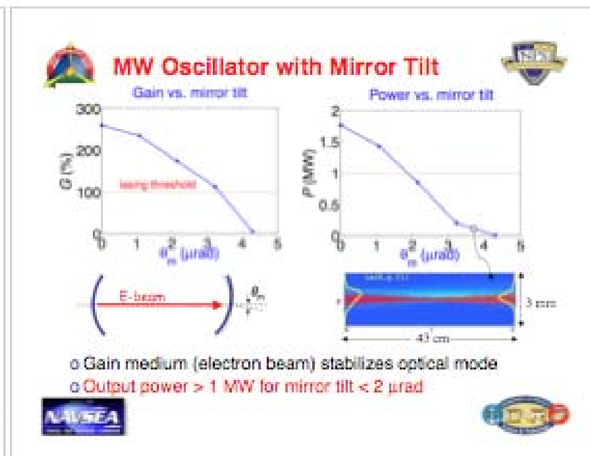

100 kW NPS Simulation
λ=1.6μm
Oscillator (3D)
o $P_b \approx$ 11MW, N =20, SRL
o slippage: $\sigma_z \approx 9 >> 1$
o G ≈ 50%, Q = 5, no taper
o $P_{out} \approx$ 350kW, $\eta \approx 3.2\%$
o S=20m, $I_{mir} \approx$ 110kW/cm²
o $\Delta\gamma/\gamma \approx$ 8%, good mode
Amplifier (4D)
o $P_b \approx$ 11MW, N =120
o slippage: $\sigma_z \approx 1.6 \sim 1$
o $P_{in} \approx$ 100W, tapered
o $P_{out} \approx$ 110kW, $\eta \approx 1\%$
o S=10m, $I_{mir} \approx$ 40kW/cm²
o $\Delta\gamma/\gamma \approx$ 5%, OK mode
τ=1
τ=0
τ=0
τ=1

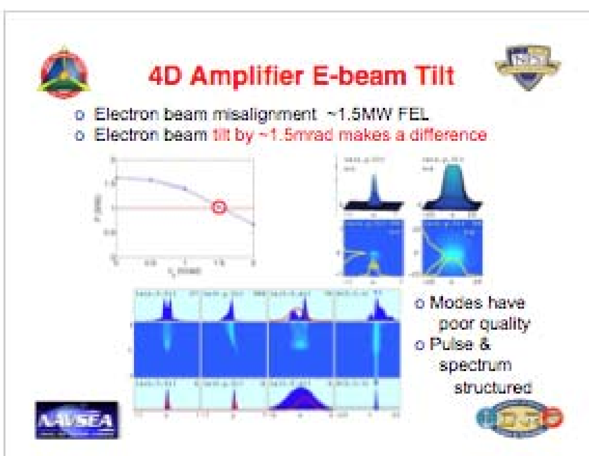

1 MW NPS Simulation
λ=1.6μm
Oscillator (3D)
o $P_b \approx$ 45MW, N =20, SRL
o slippage: $\sigma_z \approx 9 >> 1$
o G ≈ 350%, Q = 2, no taper
o $P_{out} \approx$ 1.5MW, $\eta \approx 3.4\%$
o S=20m, $I_{mir} \approx$ 95kW/cm²
o $\Delta\gamma/\gamma \approx$ 10%, good mode
Amplifier (4D)
o $P_b \approx$ 45MW, N =100
o slippage: $\sigma_z \approx 2 \sim 1$
o $P_{in} \approx$ 100W, tapered
o $P_{out} \approx$ 1.6MW, $\eta \approx 3.6\%$
o S=10m, $I_{mir} \approx$ 210kW/cm²
o $\Delta\gamma/\gamma \approx$ 12%, good mode
τ=1
τ=0
τ=0
τ=1

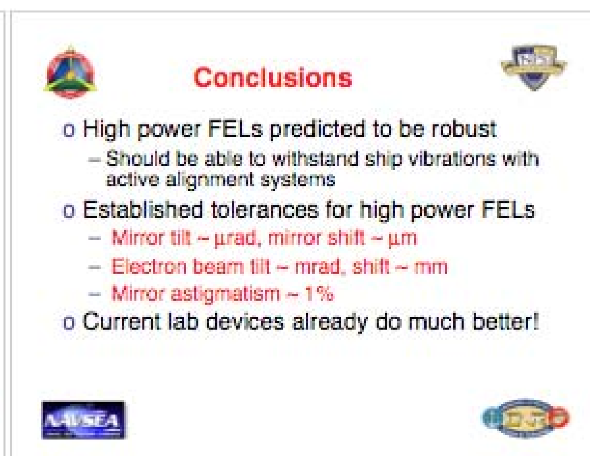

Vibration Tolerances for
Free Electron Lasers on
Naval Electric Ships
LTJG Dave Burggraff and ENS Chuck Allen, NPS
Bill Colson, Pete Crooker and Joe Blau, NPS
DEPS Systems Symposium, Monterey, CA, March 2007
NAVSEA


100 kW FEL Electron Beam Shift
100 kW
Electron Beam Radius
o LANL proposed FEL amplifier (Dinh Nguyen)
o 100 kW achieved for beam shift < 0.4 mm
o Undulator gap = 8 mm
o Experimental tolerance
Δy₀ ≈ 0.05 mm
2.4m
1.1 mm
y₀
NAVSEA


100 kW Oscillator with Mirror Shift
Extraction vs. mirror shift
E-beam
Δyₘ
4 mm
42 cm
o Gain medium (electron beam) stabilizes optical mode
o Output power > 100 kW for mirror shift < 17 µm
NAVSEA


MW Oscillator with Mirror Tilt
Gain vs. mirror tilt
Power vs. mirror tilt
G (%)
P (MW)
lasing threshold
θₘ (µrad)
E-beam
3 mm
43 cm
o Gain medium (electron beam) stabilizes optical mode
o Output power > 1 MW for mirror tilt < 2 µrad
NAVSEA


4D Amplifier E-beam Tilt
o Electron beam misalignment ~1.5MW FEL
o Electron beam tilt by ~1.5mrad makes a difference
o Modes have poor quality
o Pulse & spectrum structured
NAVSEA


Conclusions
o High power FELs predicted to be robust
– Should be able to withstand ship vibrations with active alignment systems
o Established tolerances for high power FELs
– Mirror tilt ~ µrad, mirror shift ~ µm
– Electron beam tilt ~ mrad, shift ~ mm
– Mirror astigmatism ~ 1%
o Current lab devices already do much better!
NAVSEA

LAGUERRE-GAUSSIAN MODES IN THE FREE ELECTRON LASER

by

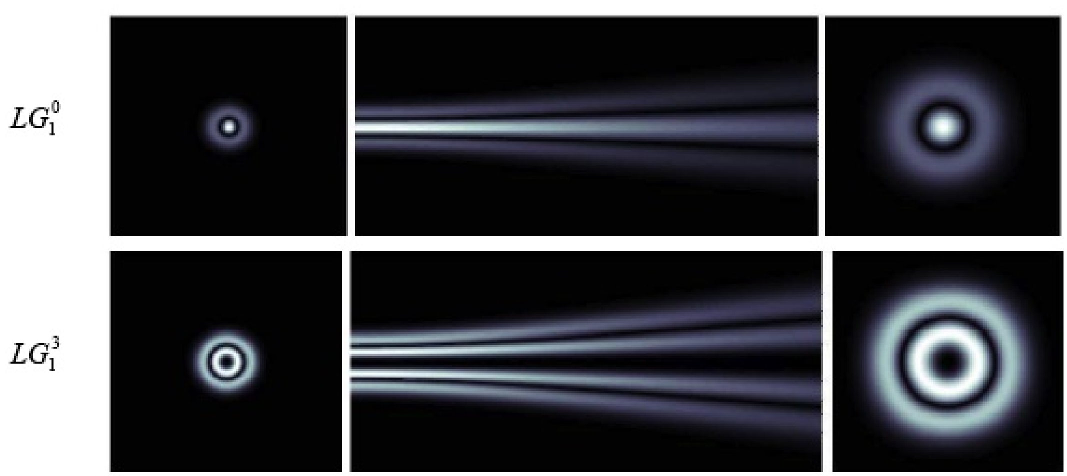
Anastasios Kampouridis

June 2007

Thesis Advisor: William B. Colson
Co-Advisor: Robert L. Armstead

In a free electron laser (FEL) system, knowing the optical beam characteristics is of great importance. A beam may be comprised of higher-order modes due to the interaction with the electron beam, or from non-ideal operational conditions such as mirror distortions and misalignments, or from imperfect injection of the electron beam.

In this thesis, the basic FEL theory is initially reviewed. The parabolic wave equation is then solved for the "fundamental" Gaussian mode and for higher-order modes. Working in rectangular coordinates, a complete and orthogonal set of solutions involving Hermite polynomials is found. When the wave equation is solved in cylindrical coordinates, we arrive at a set of solutions that contain Laguerre polynomials. The so-called Laguerre-Gaussian modes are analyzed. The evolution of these laser modes is also explored, yielding quite unexpected results due to their phase structure and orbital angular momentum of light. Lastly, we study a common case where higher-order optical modes appear, in order to quantify the tolerances of an FEL.



INTEGRATING THE FEL ON AN ALL-ELECTRIC SHIP

by

Charles A. Allen III

June 2007

Thesis Advisor: William B. Colson
Second Reader: Robert L. Armstead

This thesis examines the feasibility of placing the free electron laser (FEL) on the all-electric ship. The power required by the FEL and the tolerance of the FEL to vibrations is determined using computer simulations. Methods of reducing the vibrations using vibration isolation and active alignment are described. The simulations show that the all-electric ship will provide more than enough power to operate the FEL. The results also indicate that there must be methods to reduce the effect of ship vibrations in order for the FEL to reach the desired output power of one to three megawatts.

The thesis also describes the physical dimensions of the FEL as well as its weight and compares these figures to other ship systems. Overall the simulations and the research show that it is reasonable that a high-powered FEL can be developed for use as a weapon on the all-electric ship. While developing such a weapon will be an engineering challenge the capability to do so has been demonstrated.

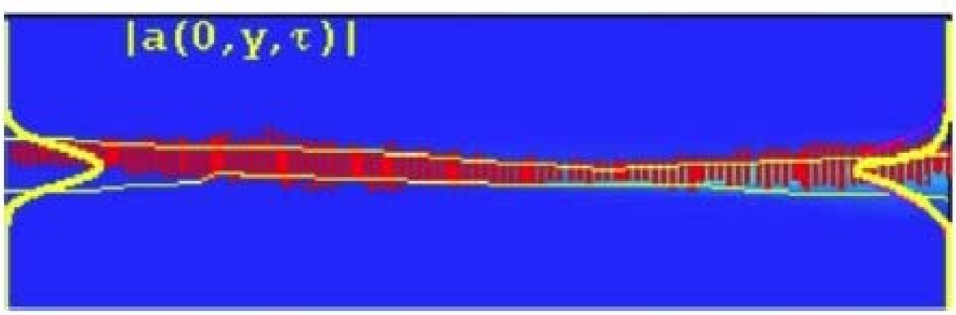


Figure 12. Optical energy in an oscillator FEL with an electron beam tilt.

FREE ELECTRON LASER PERFORMANCE WITH QUADRUPOLE MAGNET MISALIGNMENT FROM SHIPBOARD VIBRATIONS

by

David Thomas Burggraff

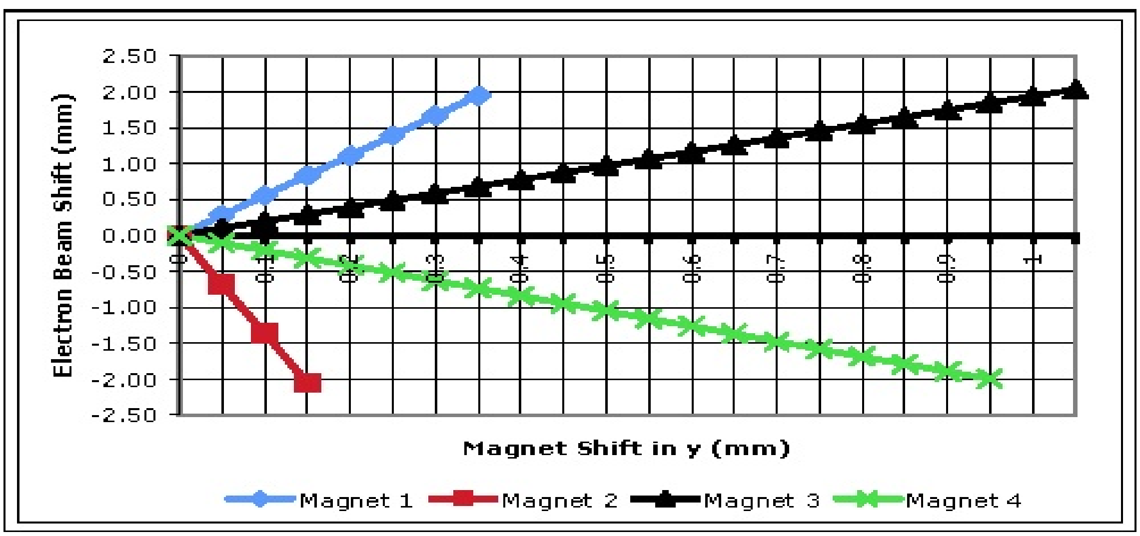
December 2007

Thesis Advisor: William B. Colson
Second Reader: John W. Lewellen

The Free Electron Laser (FEL) has been discussed and studied in the United States Navy's directed energy weapon efforts. The goal of these studies is to use the FEL as a ship's primary defensive weapon against incoming threats such as missiles, aircraft and small boats.

This thesis is an analysis of the effects of shipboard vibration on the performance of an FEL. The focus of this analysis will be on the performance degradation due to quadrupole magnet misalignments from ship vibrations and flexing.

This study is aimed at improving system design efforts by determining the sensitivity of an FEL on magnet misalignments due to shipboard vibration and flexing. Simulations were conducted on the magnets placed along the electron beam path between the end of the accelerator and the beginning of the undulator. Simulations within this study were conducted using the 3D FEL simulator designed and programmed at the Navy Postgraduate School and FELSIM designed and managed by Advanced Energy Systems.



FOUR DIMENSIONAL ANALYSIS OF FREE ELECTRON LASERS IN THE AMPLIFIER CONFIGURATION

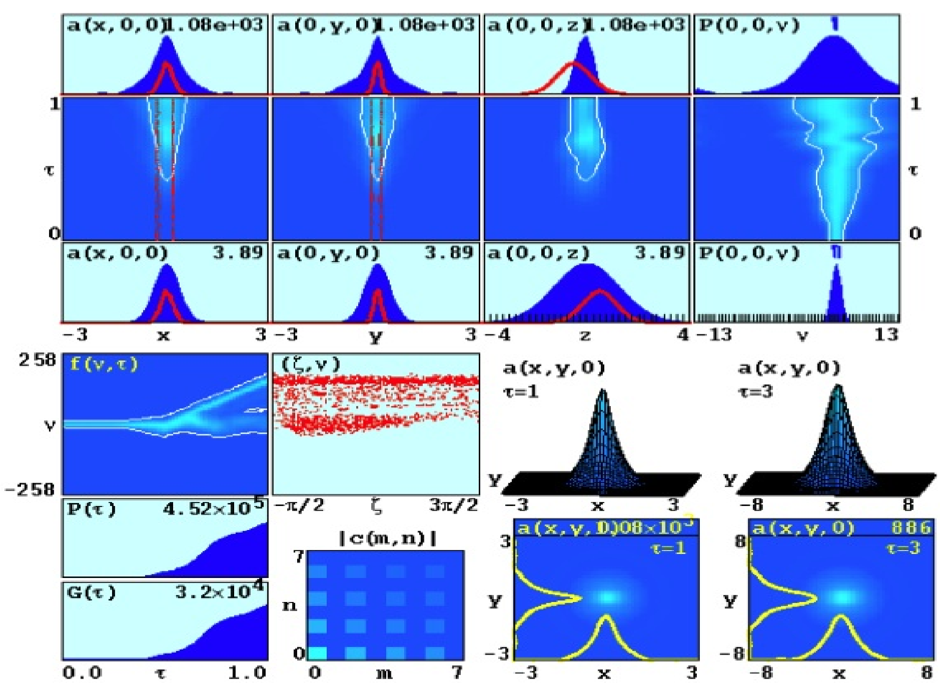
by

Juan R. Sans Aguilar

December 2007

Thesis Advisor: W. B. Colson
Second Reader: J. Blau

Free electron lasers (FEL's) are devices used worldwide for several purposes. In the military, especially in the Navy, they can be used for self-defense against missiles, and small boats. Installed on a ship, an FEL represents a multi-mission, deep magazine, long range weapon. This thesis will describe briefly the basic components and principles of operation. It also explores, by simulations, the effects of changing some of the parameters that generate the laser beam.



FREE ELECTRON LASER ANALYSIS FOR THE INNOVATIVE NAVY PROTOTYPE

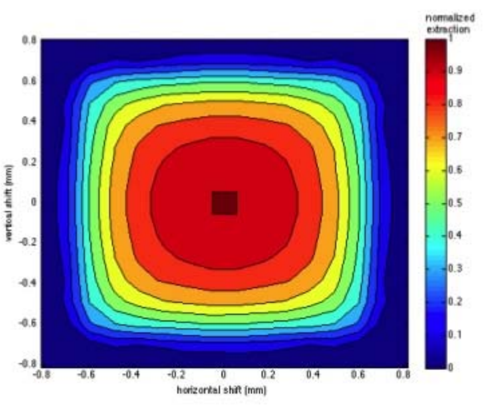
by

Darin S. Smith

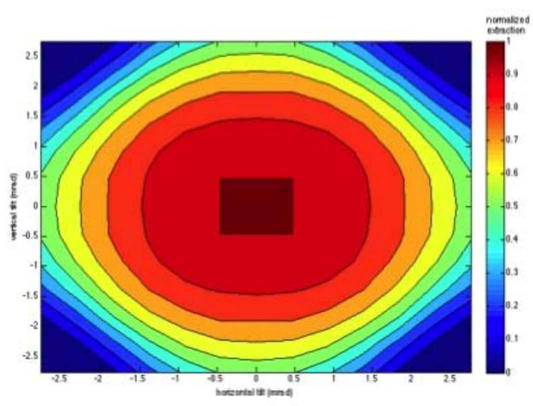
March 2008

Thesis Advisor: William B. Colson
Co-Advisor: Joseph Blau

Free Electron Lasers are the focus of a recently announce Innovative Navy Prototype to develop a directed energy weapon system for the self-defense of ships. Operating in a shipboard environment poses several challenges that must be overcome. Short Rayleigh length systems offer solutions to some of these problems. Simulations were performed to examine the benefit of short Rayleigh length designs in the face of electron beam misalignment. Additionally, simulations were performed to explore the effect of quadrupole misalignment on electron beam position and trajectory, and ultimately on FEL performance.



Normalized extraction versus horizontal and vertical shift.



Normalized extraction versus horizontal and vertical tilt.

Short Rayleigh length free electron laser: Experiments and simulations

P. P. Crooker, W. B. Colson, J. Blau, D. Burggraff, and J. Sans Aguilar
Physics Department, Naval Postgraduate School, Monterey, California 93943, USA

S. Benson, G. Neil, M. Shinn, and P. Evtushenko
Thomas Jefferson National Accelerator Laboratory, Newport News, Virginia 23606, USA
(Received 31 January 2008; published 17 September 2008)

We report experiments at Jefferson National Accelerator Facility (Jlab) and computer simulations performed at the Naval Postgraduate School (NPS) designed to probe the small Rayleigh length regime. We compare the gain, power, and sensitivity to mirror and electron beam misalignments as a function of decreasing Rayleigh length. The agreement is quite good, with experiments and simulations showing comparable trends as the Rayleigh length is decreased. In particular, we find that the gain and power *do not* decrease substantially at short Rayleigh length, contrary to a common Gaussian-mode filling factor argument. Within currently achievable alignment tolerances, the gain and power are still acceptable for FEL operation.

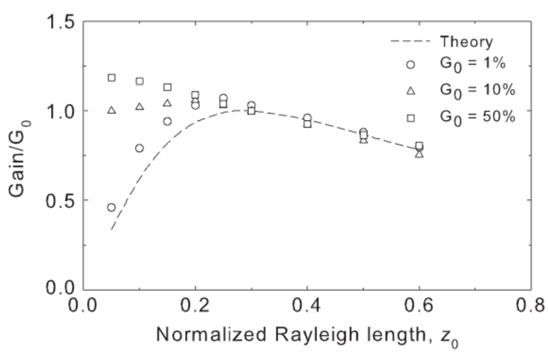


FIG. 1. Simulations of weak-field gain versus normalized z_0 for increasing values of G_0. The dashed curve is the gain predicted by Eq. (1).

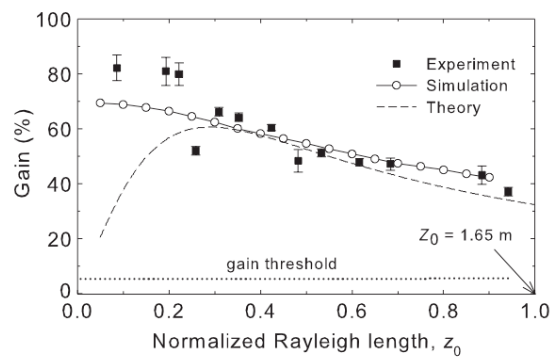


FIG. 2. Dependence of gain on normalized Rayleigh length z_0. The dashed line is derived from Eq. (1). The dotted line is the cavity loss due to output coupling (5.9%); the gain must at least overcome this loss. The dimensional Rayleigh length at $z_0 = 1$ is $Z_0 = 1.65$ m.

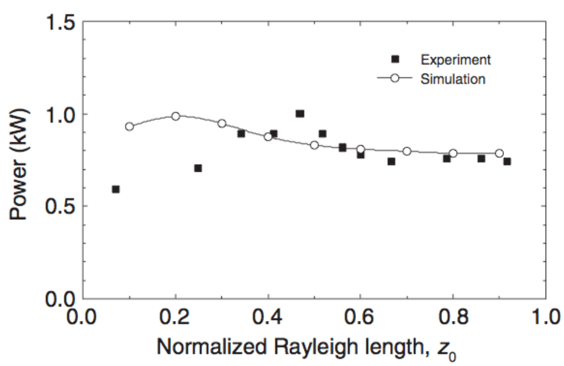


FIG. 4. Dependence of output power in a macropulse on z_0.

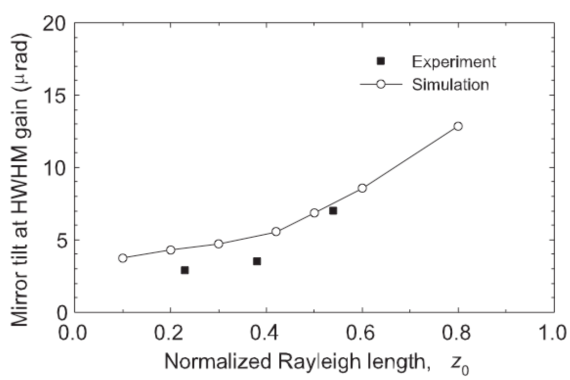


FIG. 6. Mirror tilt at HWHM gain versus z_0.

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